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The properties of underwater welded mild steel and high strength steel joints.

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THE PROPERTIES OF UNDERWATER WELDED MILD
STEEL AND HIGH STRENGTH STEEL JOINTS.

Michael Bruce Meloney

THE PROPERTIES OF UNDERWATER WELDED

MILD STEEL AND HIGH STRENGTH STEEL JOINTS

by

Michael Bruce Meloney

S.B., United States Naval Academy
1966

SUBMITTED IN PARTIAL FULFILLMENT OF THE

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THE PROPERTIES OF UNDERWATER WELDED MILD STEEL

AND HIGH STRENGTH STEEL JOINTS

by

Michael B. Meloney

Submitted in partial fulfillment of the requirements
for the degree of Ocean Engineer and the Degree of Master of
Science in Naval Architecture and Marine Engineering at the
Massachusetts Institute of Technology, June, 1973.

ABSTRACT

This thesis is divided into two parts, the first being
an investigation into the multipass underwater welding of
mild steel, and the second an investigation into the feasi-
bility of underwater welding HY-80 steel. With the former,
current underwater shielded metal-arc welding technology was
employed, while with the latter, current shielded metal-arc
air welding technology was adapted to underwater welding.

Multipass underwater mild steel welds are very often
required and are commonly employed during underwater repair
and salvage operations. However the physics, and even the
basic properties of multipass welding are not well known.
Experimental results showed that multipass underwater butt
welds can be fabricated with marginally satisfactory tensile
and impact strength. It appears that weld metal embrittle-
ment due to rapid quenching causes the weld metal to become
most susceptible to brittle fracture. This is significantly
different from air welding, where the heat affected zone is
more susceptible to brittle fracture.

There are presently a substantial number of naval vessals
afloat with all or part of their hull structure fabricated
with HY-80 steel. However no investigation has been made into
the feasibility of welding HY-80 underwater in order to per-
form voyage repairs or carry out salvage operations. Simple
lap and tee joints were fabricated underwater from HY-80
steel of various thicknesses, and tests conducted to determine
joint strength and ductility as well as overall weld quality.
Both single and multipass joints were fabricated. It was
found that acceptable joints could be fabricated, with joint
performance comparable to that of underwater welded mild
steel joints.

Thesis Supervisor: Professor K. Masubuchi
Title: Professor of Ocean Engineering

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CHAPTER I - INTRODUCTION

This report is divided into two parts, the first being
an investigation into the multipass underwater welding of
mild steel, and the second an investigation into the
feasibility of underwater welding HY-80 steel. With the
former, current underwater shielded metal-arc welding tech-
nology was employed, while with the latter current shielded
metal-arc air welding technology was adapted to underwater
welding.

Shielded metal-arc underwater welding has been the most
studied underwater welding process to date, however the
depth of knowledge of this process is still superficial.
The shielded metal-arc process has proven satisfactory for
the underwater repair and salvage of ships since World War II,
but now industry needs the capability to fabricate steel
structures underwater, as well as maintain them. Tremendous
savings could be made if undersea pipelines, offshore oil
towers and other ocean structures could be fabricated in
place by a wet welding process. This current commercial
need has spurred great interest not only in developing such
a wet welding process, but in understanding the physical
processes and phenomena of underwater welding in general.

Part one of this report evaluates some of the properties
of multipass shielded metal-arc underwater welds. Multipass

welds are very often recommended[1] or required during under-
water repair welding due to poor joint fit-up, thick plating,
etc., and are therefore commonly employed actual underwater
repair and salvage operations. However the physics, and
even the basic properties of multipass welding are not well
known. Grubbs[2] in 1971 reported success by the Chicago
Bridge and Iron Company in producing sound multipass under-
water SMA welds but this was the only reference found which
investigated any aspect of multipass welding.

Part two of this report was an initial investigation
into the feasibility of welding HY-80 steel joints underwater.
The U.S. Navy has almost two decades of experience in the air
welding of HY-80 plate for submarine hulls. Its large
strength to weight ratio, plus good weldability under
controlled conditions makes HY-80 steel an obvious choice
as a surface ship hull material. There are presently a
substantial number of naval vessels afloat with all or part
of their hull structure fabricated with HY-80 steel. Their
exceptional performance will increase the use of this
material in future ship construction.

A literature survey revealed no published record of
any experimental or theoretical work done on the underwater

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[1] See Navy Underwater Cutting and Welding Manual
pp 6-12 to 6-15.

[2] Grubbs op. cit.

welding of any high strength steel. Verbal conversations
with the Naval Ships Systems Command welding engineer, and
the Office of the Supervisor of Salvage confirmed that no
U.S. Navy "in house" or contract study was presently going
on, or was planned on the underwater welding of HY-80 steel.
The concensus of opinion was that a high strength quenched
and tempered steel such as HY-80 could not be satisfactorily
welded underwater.

It seems prudent at this time to conduct an initial
investigation into the actual underwater weldability of
HY-80 steel for the purpose of performing emergency under-
water repairs or conducting salvage operations, through the
use of a wet fusion welding process. The main thrust of
this study was to determine the practical limits of joint
strength and ductility, as well as the overall weld quality
which is achievable in the underwater welding of HY-80 steel.

CHAPTER II- UNDERWATER WELDING OF MILD STEEL PLATE

Section A - Procedure

A1. Introduction

The purpose of this portion of the investigation was twofold. First to gain practical experience in the "art" of underwater welding under controlled laboratory conditions in order to fabricate actual fillet weld lap and tee joints underwater from HY-80 steel plate. Second to determine the tensile strength and notch toughness of multipass underwater welded butt joints and compare these values to bead-on-plate specimens and base plate properties.

A2. Underwater Welding Procedures

Welding Equipment. The welding equipment and arrangement shown in figure 1 was used for the underwater welding of both mild steel and HY-80 steel specimens, and consisted of the following:

1. water tank

2. power source with standard electrode holder

3. current, voltage, and time recorders

Water Tank. The welding experiments were conducted in a steel tank measuring four feet long by three feet high by two feet wide. The exterior of the tank was sheathed in wood and rubber matting to prevent electrical shocks. A platform, containing clamps for securing the specimen, was fitted to the inside of the tank. The platform was located

EQUIPMENT SCHEMATIC
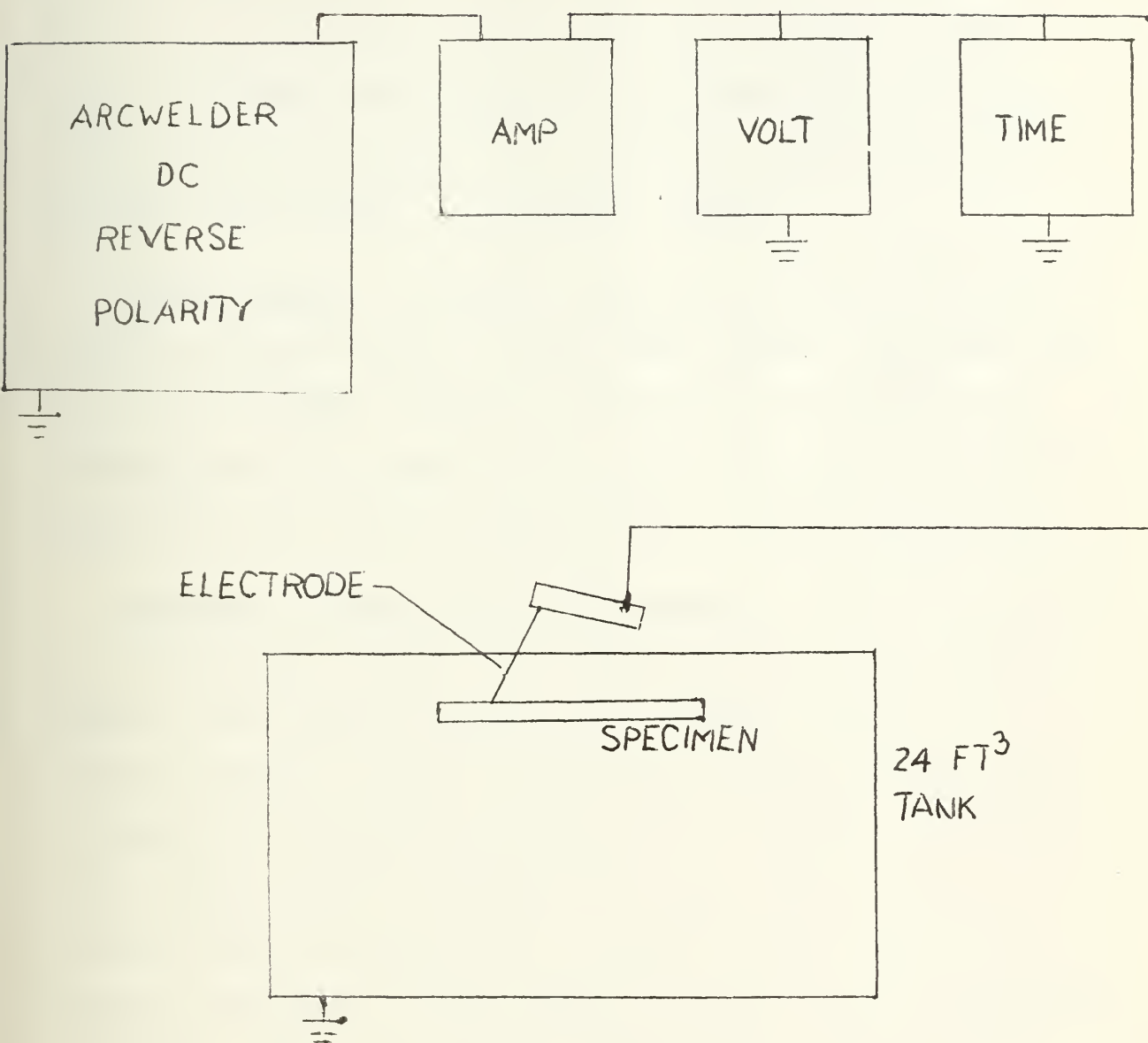
FIGURE 1

one foot from the top of the tank so that the electrode,
but not the electrode holder, would be submerged in the
water. The tank was filled by a line supplying ordinary
tap water (Boston, Mass.) and drained by gravity discharge.
The tank was grounded to the power source.

Power Source. A Lincoln Idealarc Model R3M 400 amp D.C.
welding machine was used as the power source. DCRP was used
in all experiments because of the ease in initiating and
maintaining an arc, and the less dense flux cloud produced
during welding, with no apparent loss in weld penetration.

Current, Voltage and Time Recorders. A General Electric
D-C (0.400 amp.), Model 10H, recording ammeter was used to
measure the current flowing in the welding circuit. An
Esterline Angus (0.100 V) recording voltmeter was selected
to measure the operating voltage during welding. A timing
device consisting of a General Time Co., Model 320-1,
electric clock connected to a circuit breaker was used to
measure the amount of time required to lay a given length of
weld bead. When the arc was initiated the breaker would
close and start the clock; breaking the arc would cause the
clock to stop. Dividing the length of the bead by the elapsed
time gave the electrode travel speed.

Welding Criteria. MIL-STD-00418B (SHIPS)- Mechanical
Tests For Welded Joints was used as a standard in the prepara-
tion, welding, cutting, and testing of tensile and Charpy

impact specimens.

Welding Materials. Cold rolled mild steel plate (ASTM 242) was utilized for both bead-on-plate and butt joint specimens. Tensile specimens were cut from 10" long by 6" wide by 3/16" thick welded plates. Charpy impact specimens were cut from 4" long by 4" wide by 3/4" thick welded plates. 5/32" E6013 electrodes, coated with parrafin prior to welding, were used for all mild steel underwater welds.

Welding of $\frac{1}{4}$" Mild Steel Tensile Specimens. 10"L x 6"W plates were received in a cleaned and surface primed condition. For transverse bead-on-plate welds the weld would be made accross the width of the plate, and then a number of 10" long specimens cut from the plate. For longitudinal bead-on-plate welds, three 10" x 2" strips were machine cut from each 10" x 6" plate prior to welding. For transverse butt joint specimens, each 10" x 6" plate was cut in half accross the width so that two 5"L x 6"W plates could be butt welded to the original 10" x 6" size, and then cut to proper specimen sizes.

The regions to be welded on each plate were sanded and wire brushed to remove primer paint and expose clean metal along the desired weld line. The plates were then clamped to the water tank welding tray and manually welded in 8" of fresh water, bead-on-plate welds were single pass. The ungrooved butt joints were multipass, with two full passes

made on both sides of the plates. Due to the excessive
turbidity which evolves during underwater welding it was
necessary to use a wooden straightedge as an electrode guide
in order to lay down a straight weld bead along the desired
weld line. The straightedge was easily clamped to the side
of the welding tray, and greatly facilitated the manual
welding of all the specimens.

After completing the transverse welds, 1" was cut off
each long side of the plate and discarded in order to eliminate
any edge effects in the test specimens. The remaining 10" x 4"
welded plate was then cut into two 10" x 2" pieces and
machined as shown in figure 2A.

The longitudinally welded plates were already cut to
proper size and machined as shown in figure 2B. Plate edge
effects were not significant in this case. After machining,
the weld reinforcement was ground off, but care was taken not
to eliminate weld undercut.

Welding of 3/4" Mild Steel Charpy Impact Specimens. Two
4" x 4" x 3/4" plates were prepared and butt welded in the
same manner as the $\frac{1}{4}$" transverse butt joints. Numerous
multipass welds were made in the ungrooved joint in order to
completely fill the joint. All passes were made on one side
with hand clamps preventing angular distortion of the
component plates. Each pass was hand wire brushed immediately
after welding, and after each second pass the entire unit was
removed from the tank and machine wire brushed to remove all

THESE EDGES MAY
BE FLAME CUT

T

W

$\frac{1}{4}$

$\frac{1}{4}$

IO APPROX

B

2"R

EDGE OF
WIDEST FACE
OF WELD

$\frac{1}{4}$ $\frac{1}{4}$

W=$1\frac{1}{2}$"± 0.01" IF T DOES NOT
EXCEED I".

W=I"± 0.01" IF T EXCEEDS I".

SH9220

THIS SECTION MACHINED
PREFERABLY BY MILLING
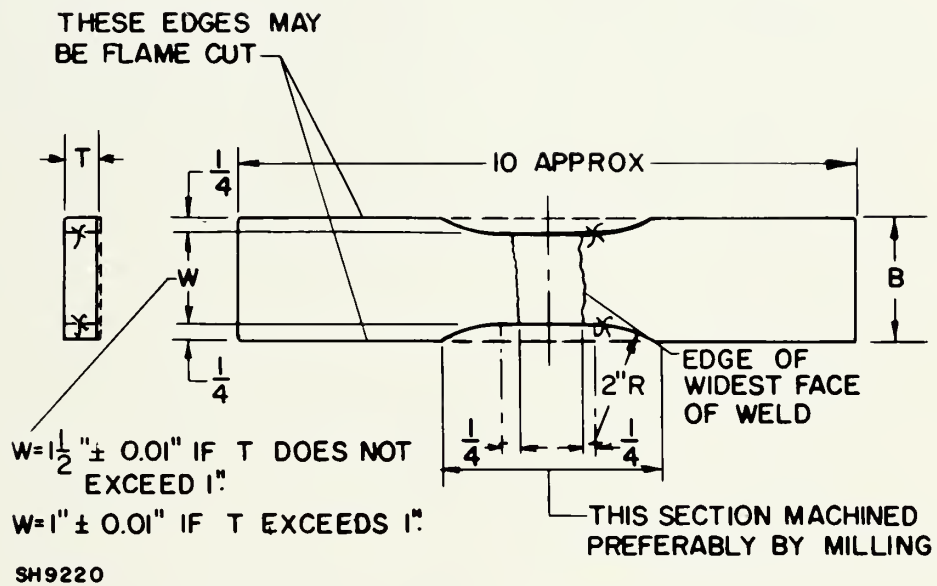
Figure 2A - Transverse tensile specimen.
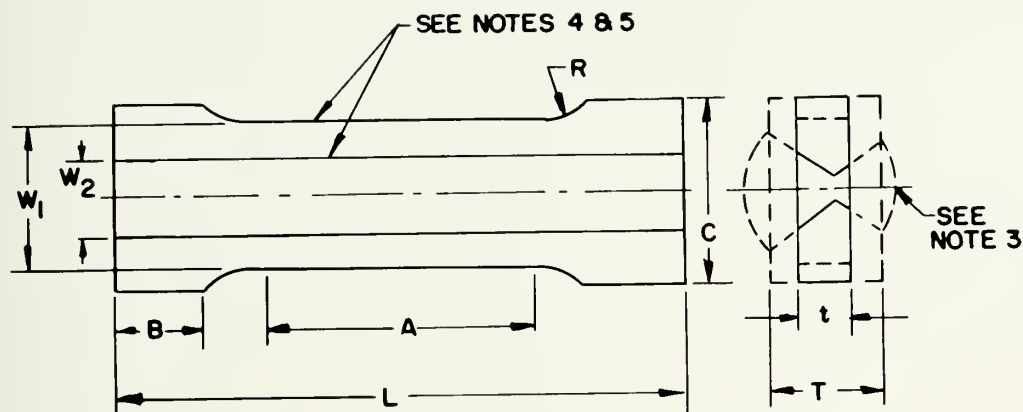
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	DIMENSIONS	
	1	2
W$_1$ - Width at center (note 5)	1±1/16 inch	1-1, 2±1/8 inch
W$_2$ - Width of weld (note 4)	1/2 W$_1$ (approx.)	1/2 W$_1$ (approx.)
T - Thickness (note 1)	Thickness of material	
t - Thickness (note 2)	Thickness of specimen	
R - Radius of fillet	1 inch, minimum	1 inch, minimum
L - Overall length	10 inch, minimum	10 inch, minimum
A - Length of reduced section	2-1/4 inch, minimum	2-1/4 inch, minimum
B - Length of grip section	3 inch, minimum	3 inch, minimum
C - Width of grip section	1-1/2 inch, approx.	2 inch, approx.

NOTES:
1. The dimension "T" is the thickness of the plate section as provided for in the applicable material specification.
2. The dimension "t" is the thickness of the specimen.
3. The weld reinforcement and backing strip, if any, shall be removed flush with the surface of the specimen.
4. The width "W$_2$" of the weld may be varied to approximate 1/2 W$_1$ by selecting an appropriate specimen thickness "t" and its location within the weld.
5. The width "W$_1$" may be varied within reason to accommodate the approximation of W$_2$ = 1/2 W$_1$ if it is not possible to meet the requirements of note 4.
6. The specimen ends shall be symmetrical with the centerline of the reduced section within 0.01 inch.
7. Remove final machining marks on reduced section surfaces with 180 grit abrasive parallel to the longitudinal direction.

Figure 2B - Longitudinal tensile specimen.

the remaining flux covering. The joint gap was approximately
two electrode diameters wide, so two full passes could be
made side by side without resulting slag entrapment. After
completion of the welding, ½" was cut off each weld end and
discarded. The weld reinforcement was ground down to the
base plate, and then 1/16" was milled off the top side of
the entire welded plate. Five Charpy specimens were then cut
from the welded butt joint. The specimens were cut perpendic-
ular to the weld bead with the center of the weld bead
coinciding with the center of the Charpy specimen. In this
way the toughness of the multipass region alone was evaluated.

Welding Parameters. The Navy Underwater Cutting and
Welding Manual gives a recommended current range for welding
underwater with E6013 electrodes. This was used as a guid-
line in initial bead-on-plate test runs. Then the range of
current settings for given travel speeds was narrowed down
and optimized for the steel thickness being welded.

The range of welding parameters used were as follows:

<u>1/4" mild steel plate</u>
Current   190-205 Amps (DCRP)
Voltage   28-33 Volts
Travel speed   11.7 - 14.5 inches/min.
Ambient temp.   39.6°F

<u>3/4" mild steel plate</u>
Current   210-230 Amps (DCRP)
Voltage   21-27 Volts
Travel speed   9.5-11.4 inches/min.
Ambient temp.   41°F

Section B - Experimental Results

Tensile tests and Charpy impact tests were conducted in accordance with MIL-STD-00418B Mechanical Tests For Welded Joints.

Tensile tests were conducted on a Baldwin hydraulic testing machine. The maximum load to failure and the fracture location were recorded, and the reduction in area and elongation measured for each specimen. Tensile strength was computed as the maximum load to failure divided by original cross-sectional area. Test results are shown in Table 1.

Charpy impact specimens were fractured on a Tinius Olsen Universal Impact Machine. Three test temperatures were used,($68^{o}F$, $32^{o}F$, and $-60^{o}F$)with three specimens fractured at each temperature. Test results are shown in Table 2.

Table 1 - Results of Mild Steel Tensile Tests

Specimen	Tensile Strength (psi)	% Elong. in 2 in.	% Reduction in Area	Fracture Location[*]
1A	65,610	9.4	12.0	W.M.
1B	60,370	7.8	11.1	W.M.
1C	64,000	9.3	12.0	W.M.
1D	66,200	9.3	11.9	W.M.
1E	54,825	12.5	11.0	W.M.
Ave Series 1	62,200	9.7	11.6	----
2A	72,210	26.9	19.3	B.M.
2B	68,925	24.2	23.4	B.M.
2C	64,710	15.9	24.5	HAZ
2D	52,840	11.9	16.3	W.M.
2E	55,140	13.0	14.6	W.M.
Ave Series 2	62,765	18.4	19.6	----
3A	49,333	6.3	9.7	W.M.
3B	51,200	9.7	11.3	W.M.
3C	27,570	3.6	6.1	W.M.
3D	43,285	7.4	9.2	W.M.
Ave Series 3	42,847	6.8	9.1	----

[*] W.M. = Weld Metal

   HAZ = Heat Affected Zone

   B.M. = Base Metal

 Series 1 = Single pass longitudinal bead-on-plate.

 Series 2 = Single pass transverse bead-on-plate.

 Series 3 = Multipass transverse butt weld.

Table 2 - Results of Multipass Mild Steel Charpy Impact Tests

Specimen	Temperature (°F)	Impact Energy (ft-lbs.)
4A	63°F	28.0
4B	63°F	28.2
4C	63°F	26.1
Ave	63°F	27.4
4D	32°F	20.0
4E	32°F	13.5
4F	32°F	11.7
Ave	32°F	15.1
4G	-60°F	7.6
4H	-60°F	6.4
4I	-60°F	8.0
Ave	-60°F	7.3

Section C – Discussion of Results

C1.   Bead-on-Plate Tensile Tests

Weld penetration in the longitudinal and transverse
bead-on-plate specimens extended down to about two-thirds
the plate thickness. However even with this deep penetra-
tion, specimen behavior during testing approached that of
unwelded base plate rather than that of welded butt joints.

Transverse bead-on-plate specimens showed the best
strength and ductility of the three specimens tested. This
is surprising in view of the fact that these specimens were
loaded in a direction perpendicular to weld undercut, and
therefore undercut notch effects should have caused premature
failure. Instead these specimens performed significantly
better than the longitudinal bead-on-plate welds which were
loaded in parallel to weld undercut notches, and thus failed
by a means other than root crack initiation and propagation.

In the longitudinal weld specimens, all zones of the
weld strain equally and simultaneously. The region with the
poorest ductility will therefore initiate fracture below the
ultimate tensile strength of the surrounding base metal. All
fractures in these specimens initiated in the weld metal
bead. The conclusion then is that for underwater welded mild
steel, weld metal embrittlement rather than weld undercut
will initiate premature, catastrophic failure.

C2.   Butt Joint Tensile Tests

Comparison of butt weld   test results to bead-on-plate

test results indicates that bead-on-plate specimens do not simulate actual butt joint behavior very well. No matter how deep the bead-on-plate weld penetration may be, there will still be some base metal below the weld bead which will significantly alter test results.

Transverse multipass butt joints had 68% the tensile strength and only 42% the ductility of the transverse bead-on-plate specimens, whereas the bead-on-plate specimens had 95.2% the tensile strength and 74% the ductility of ASTM 242 base plate. In addition the butt joints all failed through the weld metal, as predicted by the longitudinal specimen test results, while the transverse bead-on-plate specimens failed in all three regions without preference.

Series 3 results correlate very well with the work of Grubbs[3] who also tested the tensile and impact properties of multipass underwater welded mild steel. This leads to the conclusion that the extensive bead-on-plate underwater welding investigation carried out by Silva[4] does not give a good indication of actual underwater welded joint performance.

C7. Charpy Tests

Results of impact tests show that the multipas underwater welds met the minimum Charpy impact values for marine steels (i.e. 10-15 ft-lb minimum at $32^{o}F$)[5] The brittle fracture

[3] Grubbs op. cit.
[4] Silva op. cit.
[5] Cohen op. cit. pp1

transition temperature is just about at $32^\circ F$ which makes the welds barely satisfactory for use in the coldest ocean water regions.

Again Charpy impact test results correlate well with the work of Grubbs.[*] except for the higher value at $30^\circ F$ which indicates a significantly lower transition temperature (about $0^\circ F$) for his welds.

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[*]Multipass underwater weld Charpy impact values were:

  24 ft-lb at $70^\circ F$

  22 ft-lb at $30^\circ F$

  10 ft-lb at $-30^\circ F$

Section D - Conclusions and Recommendations

on the Underwater Welding of Mild Steel

D1. Conclusions

a. Satisfactory multipass underwater welded butt joints can be fabricated. However joint strength could be significantly improved by increasing weld metal and heat affected zone ductility, and decreasing weld undercut. Weld zone ductility can be increased by reducing the severe quenching effect of the aqueous environment and thereby improving weld zone micro-structure. Undercut can be reduced through improved welding technique and optimization of welding parameters.

   Improving weld zone grain structure will also increase joint notch toughness.

b. Porosity was not a significant problem either in single pass bead-on-plate welds or in multipass butt joints.

c. Bead-on-plate tensile specimens indicated the weakest regions in the underwater weld zone (i.e. weld metal, and undercut notch root) where premature fracture is most likely to occur. However bead-on-plate specimens did not give a valid indication of actual butt joint performance.

d. Excessive turbidity created in the water during welding made proper placing of the bead extremely difficult,

especially in the welding of thin plate butt joints
where a close fit up leaves no groove to guide the
electrode along the desired weld line. In multipass
welding, a wider joint gap can be used which provides
better guidance for the welder.

D2. Recommendations

a. There is a need to investigate the performance of
underwater welded joints which are welded in the
vertical and overhead positions. All literature
references cited in this report, except Grubbs,
investigated the quality of underwater welds made in
the horizontal position only. This makes laboratory
work easier, but is highly restrictive in the applic-
ability of test results to actual underwater welding,
where most welding is done in positions other than
horizontal. In fact, most operational welding is
done on curved surfaces (i.e. ship hulls, pipelines,
etc.) where the welding position is continually
changing. The weldability of such curved joints may
vary with welding position.

b. Use of a welding shroud to reduce the quenching effect
of the water environment has been shown to be beneficial
by Silva[6]. Further study on the effects and design of

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[6]Silva, op. cit. pp 40-75

welding shrouds for all position welding is needed.

c. The possibility of tempering the most brittle regions
    of the underwater weld zone needs to be investigated.
    Oxy-hydrogen and Oxy-MAPP torches, or Burning Bars
    could be used for this purpose. Research and develop-
    ment of effective tempering techniques for underwater
    welds will bring the highest return in increased
    joint performance per dollar invested.

d. Further investigation on the best combinations of
    welding parameters and welding technique for minimizing
    weld undercut is needed. Simple shrouds can be used
    to reduce undercut in the horizontal welding position,
    but will not be effective in vertical and overhead
    shielded metal arc welding. Optimization of welding
    parameters and techniques will be effective in reducing
    undercut in all welding positions.

CHAPTER III- UNDERWATER WELDING OF HY-80 STEEL

Section A - Procedure

A1. Introduction

The purpose of this investigation was to determine the feasibility of welding HY-80 steel plate underwater in order to fabricate joints of reasonable quality and strength for temporary repairs such as interim (voyage) repairs or for use during salvage operations. The general approach taken was to compare specific properties of simple underwater welded joints with the same joint configuration welded in air. Joints were fabricated and specimens prepared and tested in accordance with Department of Defense MIL-STD-00418B Mechanical Tests for Welded Joints and with MIL-S-16216H Fabrication, Welding and Inspection of HY-80 Submarine Hulls.

Fillet-weld lap joints, tee-bend joints and tee-tensile joints were fabricated with $\frac{1}{4}$" HY-80 plate in air and underwater, and the specimens tested and compared. Also 3/4" tee-bend joints and tee-tensile joints were fabricated underwater, with specimens cut and tested. Randomly selected air and underwater welded specimens were metallographically examined and microhardness tested to better determine the overall weldability and weld quality of the underwater welded joints compared to air-welded HY-80 plate.

The same welding equipment and set-up used for the underwater welding of mild steel was used for the underwater

welding of the HY-80 steel. The HY-80 air welds were per-
formed on a welding workstand using the same power source.
1/4" and 3/4" rolled HY-80 plate and 1/8" diameter E11018
and E310-16 electrodes, heated in holding ovens for a minimum
of four hours, were utilized. Both electrodes were hand
coated with a thin coat of paraffin after cooling and prior
to welding.

Determination of Welding Parameters. Since no references
exist which give recommended welding parameters for the under-
water welding of HY-80 steel, a trial and error method was
employed with underwater bead-on-plate welds to obtain a
range of values suitable for the plate thickness and elec-
trode diameter being used. For the Lincoln Idealarc Model
R3M 400 D.C. welding machine there is no separate voltage
setting. Voltage is preset in the machine to vary pro-
portionally, with current, as the current setting is adjusted.
Therefore as a first cut the range of values determined were
current setting required to initiate and maintain an arc,
utilizing the drag welding technique (lower limit), and
current setting which caused burnthrough (upper limit) using
a 1/8" diameter E11018 electrode. Practice runs were then
made with actual fillet-weld lap joints and tee joints in
order to firstly accustom the author to "feel" the joint and
place the weld bead along the desired line even with ex-
cessive turbidity, and secondly to narrow down the range of
welding variables, in this case current and travel speed,

so as to maximize joint penetration while minimizing weld

undercut. In all cases the maximum heat input was well

below the maximum allowable heat input for 1/4" and 3/4"

HY-80 plate listed in appendix A.

A2. Welding of 1/4" HY-80 Fillet Weld Shear Specimens

Transverse fillet shear specimens were cut from welded

plates as shown in figure 3. The component plates were

received in a cleaned and surface primed condition. The

plates were cut to size and the joint areas were pneumatic-

ally sanded and machine wire brushed to remove all primer

paint and expose clean base metal. The component plates

were then assembled in position in the water tank welding

tray and the assembly clamped to the welding tray with two

large hand clamps. The tank was then filled with fresh

water to a level 8 inches above the top plate of assembly

and welds were made with 1/8" E11018 electrodes.

Welding Sequence. The sequence of welding was one pass

on each of the two top lap joints, then the assembly was

turned over and reclamped, and one pass was made on each of

the remaining two lap joints. After each pass the weld

bead was manually wire brushed to remove the soft, powdery

flux covering, which was similar in nature to the quality

of the mild steel (E6013) flux covering described in section II

A1 . On multipass welds the welded assembly was removed

from the tank after the first set of passes was completed

and extensively machine wire brushed to remove pockets of
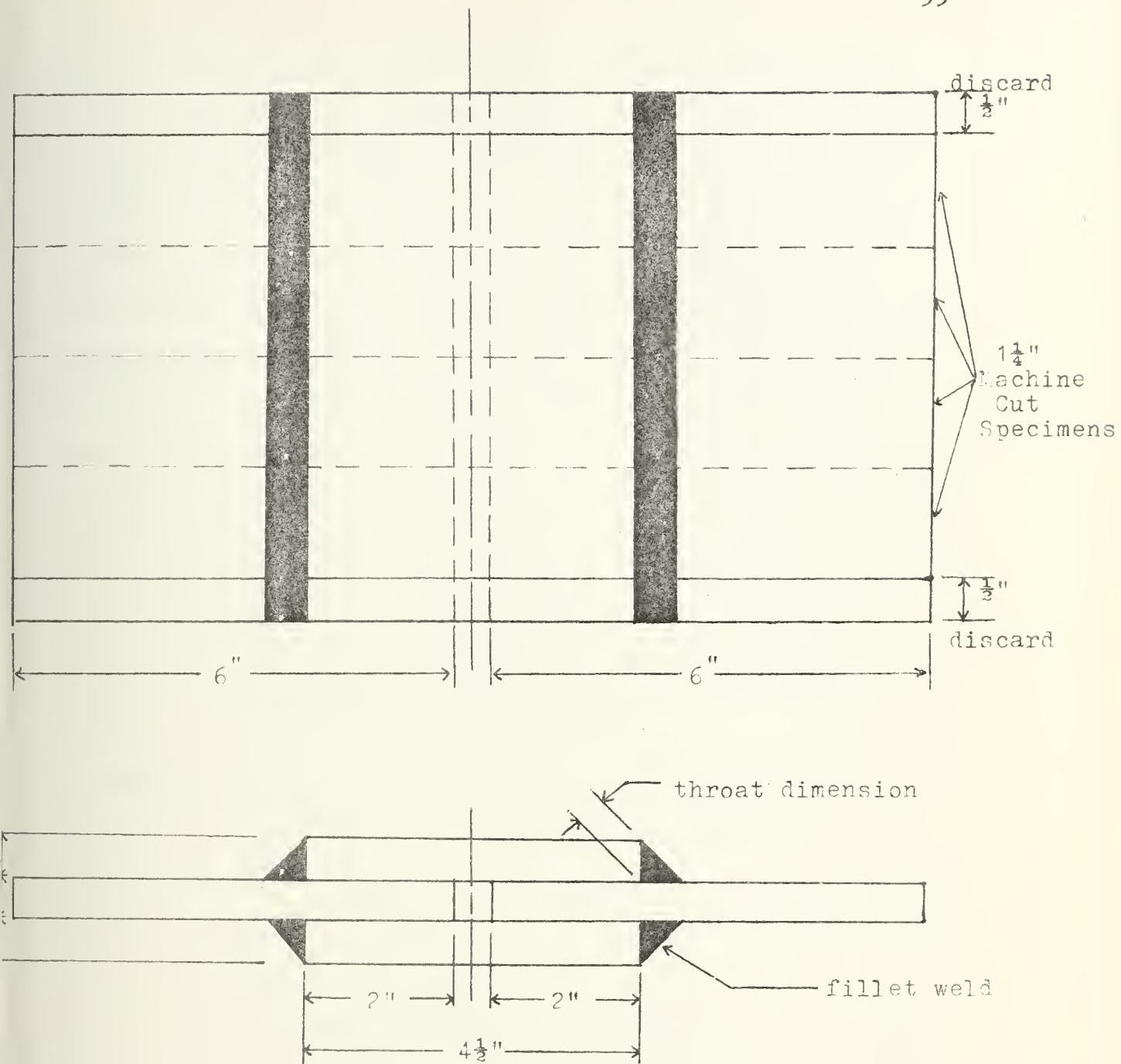
Figure 5 - Transverse fillet-weld shear specimen.

flux entrapped in the undercut roots or in surface pores. The assembly was then returned to the water tank, placed on the welding tray unclamped and welded in reverse sequence from the first set of welds, i.e. the joint last welded on the first pass was the first joint welded on the second pass, and so on. This procedure plus the constraining force of the clamps effectively eliminated weld distortion and plate separation. The clamping method was preferred over tack welding because a tack weld would have caused some slag entrapment under the covering plates along the joint which could adversely effect weld fusion in the region of the tack weld. Also a tack weld would have caused local metallo-graphic perturbations which would have unnecessarily complicated an already complex problem.

Surface Defects. Two full passes per lap joint were made in the multipass welds. However the amount and size of surface porosity caused by the second pass was many times worse than that of a single pass. Even making a single pass, and then delaying the placement of the second pass for up to 48 hours did not appreciably decrease the surface porosity problem caused by hydrogen entrapment and diffusion through the weld metal. Ordinarily surface porosity is considered a second order problem compared to undercut in its effect on weld strength and toughness. However in the case of underwater multi-pass welding of ¼" HY-80 plate with E11018 electrodes the effects

of surface cavities (and subsurface porosity) could be
significant through an inordinately large decrease in weld
crossectional area and in allowing the water environment
access deep into the weld metal, where accelerated corrosion
can occur through the formation of differential aeration
cells. This would eventually cause extensive local corrosion
through the heat effected zone and into the base metal.
This latter problem is especially significant in a marine
environment, and therefore weld bead "tightness" is essential
in underwater welding.

Repair Welds. Although these shear welds were removed
from the water after welding and were to be tested in air,
the author considered it essential to determine the extent
to which the worst cases of surface porosity could be
eliminated. The deepest pores in each bead were ground
down to the weld root with a small hand-held pneumatic
grinding wheel and then machine wire brushed. The welded
assembly was then placed back in the tank and short linear
"repair" passes were made over the ground down areas.
Usually only one such pass was needed unless the "repair"
weld bead was not placed exactly on target, in which case
the area was manually wire brushed in the tank and another
bead placed over the area. Due to poor visibility present
even in 3 inches of water, it was impossible to tell if the
bead was placed correctly until after brushing away the flux
and waiting about 15 seconds for the water to clear. After

extensive practice the author was able to place these "repair"
welds with about 75% accuracy, without producing arc craters
in the surrounding sound weld metal. Therefore such local
fusion repairs are feasible for large surface defects which
inevitably occur in the underwater multipass welding of
HY-80. It should be mentioned here however that such large
defects requiring this type of extensive repair were fairly
uncommon.

Austenitic Stainless Steel Electrodes. Grubbs[7] et al,
reported success in reducing hydrogen trapping and cracking
problems through the use of austenitic stainless steel
electrodes in the underwater multipass welding of high carbon
equivalent ($CE^* > 0.40$) structural grade steels. In welding
underwater, rapid quenching retards the diffusion rate of
hydrogen entrapped in the weldment. Austenitic stainless
steel electrodes can often decrease the hydrogen problem by
storing large quantities of hydrogen in the weld metal,
keeping hydrogen away from the crack sensitive heat affected
zone and additionally reducing the porosity problem.

Since $\frac{1}{4}$" HY-80 has a carbon equivalent of 0.546 (chemical
composition varies with thickness), it was decided to attempt
the underwater welding of $\frac{1}{4}$" HY-80 shear fillet weld specimens
with a suitable austenitic stainless steel electrode as a

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[7] Grubbs, et al, op. cit.

$CE^* = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$

back-up in case for some reason the E11018 electrode welds

proved unsatisfactory during testing. Plates were prepared,

assembled and welded with 1/8" E310-16 electrodes as

previously described for the E11018 electrode welded plates.

The E310-16 welds were all two pass welds. The weld beads

of both the first and second passes were of excellent

quality with minimal undercut and very little surface

porosity. The bead was smooth and regular and was very

similar in appearance to air welded specimens welded with

E11018 electrodes. (See figure 4). No surface grinding or

spot repairs of any kind were required. The interesting

aspect of underwater welding with E310-16 electrodes was

that, although the stainless steel electrodes have a much

lower melting point than E11018 electrodes, nearly the same

welding current and voltage was required to initiate and

maintain the arc. The electrode melted at a much higher

rate, and the end portion of the electrode which remained

out of the water turned cherry red after about ten seconds

of welding. This caused the electrode to bend severely

so that it had to be discarded after about 20 seconds of

welding. This problem would not occur in operational

underwater welding where the entire electrode is immersed,

however a high electrode travel speed would still have to be

used to avoid excessive bead size and to prevent melting of

the top lap plate edges. Opacity of the flux cloud was

similar to that of the E11018 electrode, however the flux

covering over the weld bead was very powdery and could
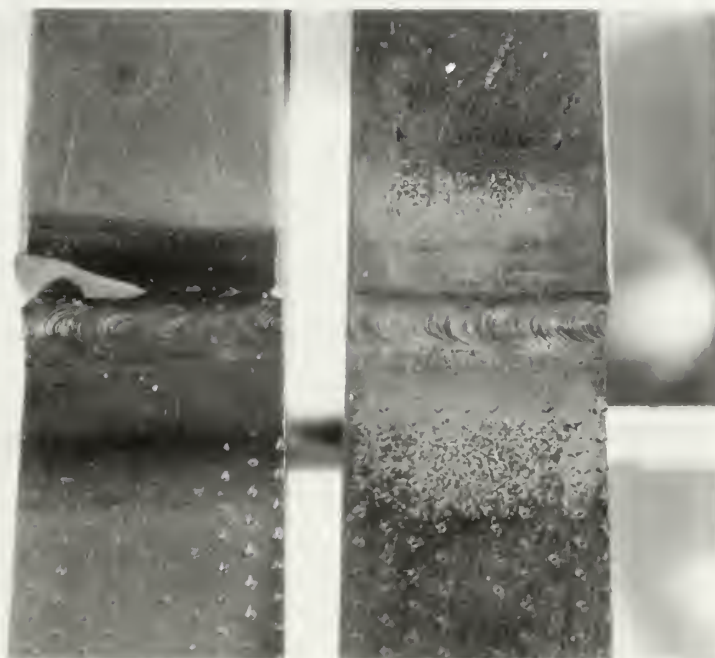
Figure 4 - Single pass underwater lap weld with E310-16 electrode (left) verses single pass air lap weld with E11018 electrode (right). Upper left corner of E310-16 weld was ground down to eliminate an arc crater caused by an interruption in the weld bead.

easily be removed by hand rubbing.

Welding Parameters. The range of welding parameters
used in the underwater welding of fillet weld shear specimens
were as follows:

> E11018 electrode
> current   180-210 Amps (DCRP)
> voltage   28-36 Volts
> travel speed   9.8-12.1 inches/min.
> heat input   32,132-36,020 Joules/in.
> ambient temp.   43.6°F
>
> E310-16 electrode
> current   160-180 Amps (DCRP)
> voltage   35-39 Volts
> travel speed   10.6-13.7 inches/min.
> heat input   27,328-35,660 Joules/sec.
> ambient temp.   44.1°F

All welds were made in fresh water using the electrode
drag technique. Plate assemblies were at ambient water
temperature for all single pass and multipass welds (interpass
temp. = ambient temp). The same power settings were used
for single and multipass welds, with only travel speed being
varied.

Joint Inspection. Immediately after welding, the plates
were carefully visually examined for surface cracking
(i. . longitudinal, transverse, crater cracking) under a
5X viewing glass. The welded plate was then stored on a
laboratory shelf for a minimum of 7 days, then visually

examined again and cut into 1½" specimens on a heavy duty
hydraulic band saw. No case of surface cracking (immediate
or delayed) was found through visual observation. In addi-
tion a dye penetrant test was conducted on a randomly
selected plate prior to cutting into specimens. All four
E11018 beads showed no case of surface cracking. Substructure
characteristics will be discussed later.

Air Welded Specimens. For comparison with the under-
water welded specimens, identical shear fillet weld specimens
were air welded both by the author and by a qualified HY-80
welder. The plates were prepared, and assembled in the same
way as the underwater welded plates, and were then welded on
a standard welding workstand. One assembly was single pass
welded by the author, another was single pass welded by a
qualified HY-80 welder. The assemblies were not preheated*
or postheated. Interpass temperatures, although not
measured, were quite high, i.e. all four joints were welded
consecutively without any cooling period between welds.
E11018 electrodes were used with a weaving gap welding
technique.

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* Minimum preheat temperature for ½" HY-80 steel plate
is 125°F.

The range of electrode parameters for the air welds were as follows:

E11018 electrode

current	120-135 Amps (DCRP)
voltage	43-48 Volts
travel speed	8.0-13.3 inches/min.
heat input	25,985-43,537 Joules/in.
ambient temp.	72.5°F

A3. Welding of 1" HY-80 Tee Joints

Tee joint specimens used for tee-bend tests and tee-tensile tests were cut from welded plates as shown in figure 5. Six specimens were cut from each plate, with three being used as tee-bend specimens and three as tee- tensile specimens. The plates were cut to size and the joint areas were pneumatically sanded and machine wire brushed to remove all primer paint and expose clean base metal. The component plates were then positioned together on a workbench and two large hand clamps were used to hold the vertical plate at 90° to the base plate. No machining of the joint was made so that the bottom edge of the vertical plate lay flush against the base plate (see figure 5). The assembly was then placed in the water tank welding tray, with the base plate positioned at a 45° angle to the horizontal welding tray to facilitate welding. The tank was filled and the joints welded with 1/8" E11018 electrodes in 8 inches of fresh water. Both single and multipass welds were made. Weldments were hand wire brushed and then machine wire

Figure 5 - Tee-bend and tee-tensile specimens.

Figure 5 - Tee-bend and tee-tensile specimens.
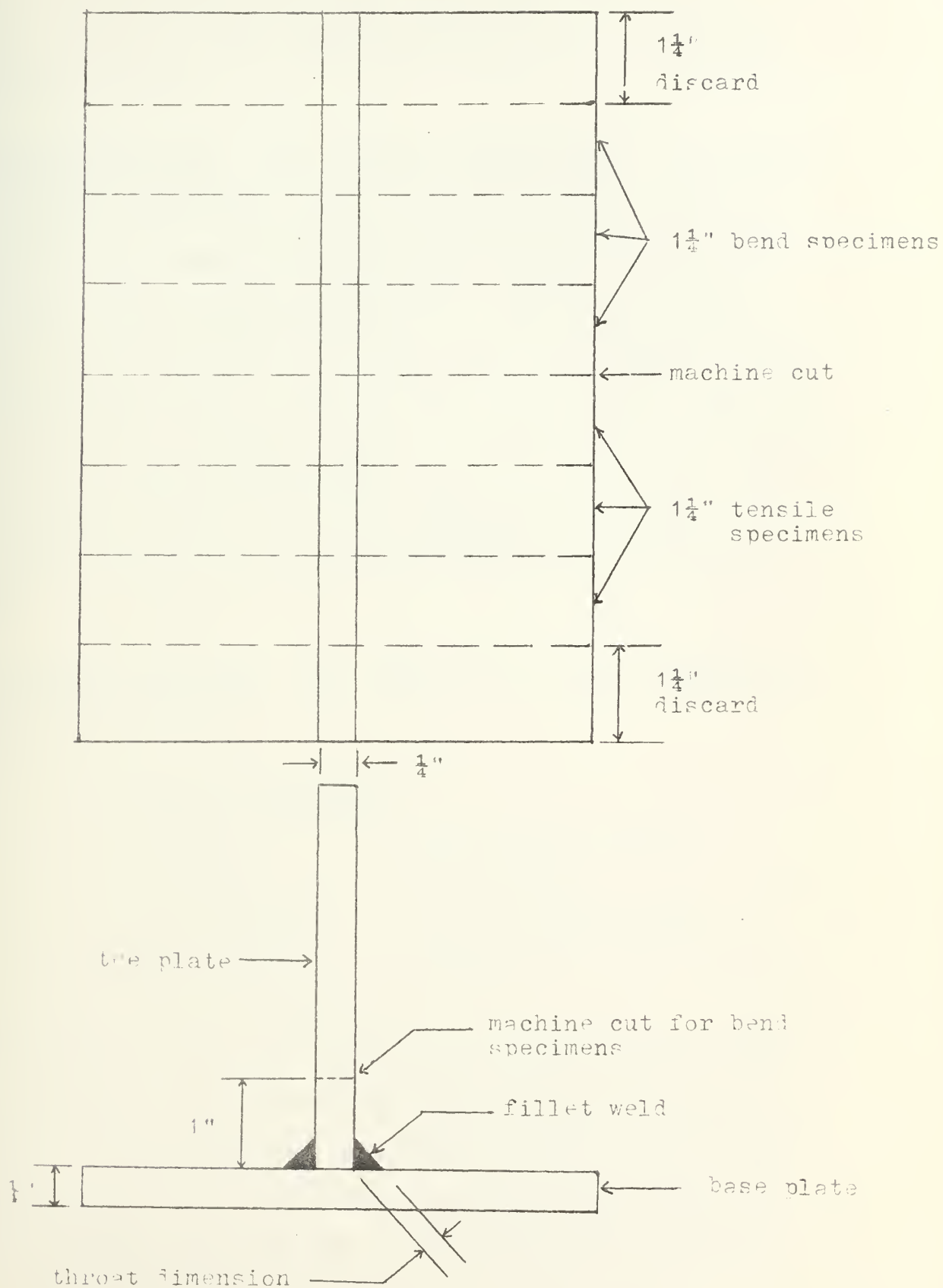
brushed between passes, and the second pass was made in opposite sequence to the first pass as in the case of the shear fillet welds.

Surface Defects. Both single and multipass welds were made with the same power inputs as the shear lap welds but at higher travel speeds with resultant smaller bead sizes and somewhat less joint penetration. Undercut was about the same as for the shear lap specimens, but surface porosity was significantly less in size, depth and density. The weld beads were so much improved that no grinding or spot repairing were required, however weld bead appearance was still of much lower quality than the E310-16 electrode welded lap joints.

Welding Parameters. The range of electrode parameters used were as follows:

E11018 electrode
current   180-210 Amps (DCRP)
voltage   28-36 Volts
travel speed   10.9-13.7 inches/min.
heat input   28,380-32,367 Joules/in.
ambient temp.   43.9°F

The welded plates were visually examined in the same manner described in section A2 before being cut into 1¼" specimens. In cutting the specimens for tee-tensile tests the vertical tee was left intact in order to fit into the tensile testing machine grips. On the tee-bend specimens,

the vertical tee was cut approximately 1 inch above the
base plate so that the specimen would fit into the bend
testing machine.

Air Welded Specimens. Single and multipass tee joints
were similarily prepared and assembled, and air welded using
1/8" E11018 electrodes for comparison with the underwater
welded specimens. No preheat, postheat or interpass cooling
was utilized.

The range of electrode parameters used were as follows:

E11018 electrode
current   120-135 Amps (DCRP)
voltage   43-48 Volts
travel speed   8.5-14.2 inches/min.
heat input   24,338-40,976 Joules/in.
ambient temp.   72°F

A4. Welding of 3/4" HY-80 Tee Joints

Time did not permit the welding and testing of 3/4"
fillet weld shear specimens, however a series of tee-bend
and tee-tensile tests were conducted on 3/4" HY-80 underwater
welded tee joints. The plate dimensions were 12" x 4 3/4"
with a double beveled web, as shown in figure 35, to insure
adequate penetration. The plates were prepared and assembled
in the same way as the ¼" HY-80 tee-joints* and welded in
2 inches of fresh water with 1/8" diameter E11018 electrodes.

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*See Section A2.

Welding Sequence.   Four to five passes per side were made.   A full pass was made on one side of the web, then a full pass on the other side.   Each pass was hand wire brushed immediately after welding, with the entire assembly being removed from the tank and machine wire brushed after each set of passes.   The assembly was then replaced in the tank and the next set of passes made in opposite sequence to the preceeding set.   Hand clamps were attached to the plates throughout the entire welding operation.   After the second and fourth set of passes both sides of the web were ground down with a hand held pneumatic grinder.   The fillet weld reinforcement was ground to a 45° angle, removing most of the surface cavities in the process.   After grinding down the fourth set of passes, isolated repair welds were made to remove the deepest pits which remained.

Weaving Drag Welding Technique.   As mentioned in Section A2, an electrode weaving technique was used to good advantage in the air welding of ½" HY-80 tee joints.   On the final pass of the 3/4" HY-80 underwater tee joint fabrication a weaving motion was employed with the electrode drag method to determine if a weaving technique could be as advantageous in the underwater welding of relatively thick plate as it proved to be in air welding.   Of course in welding any beveled joint, the electrode is physically restrained from weaving during the first few passes where the machined groove is quite narrow.   However on the outer portion of the beveled joint the groove becomes wide enough so that the electrode

can be manually maneuvered. During air welding, the molten
weld remains fluid long enough to fill in all the gaps caused
by a weaving electrode motion. In underwater welding the
molten weld metal is quenched so fast that the weld bead
cannot flow and fill in all the gaps. The result is a weld
bead ribbon that weaves back and forth accross the joint like
a sine wave, so that another weld bead ribbon must be laid
"180° out" from the first in order to completely fill in the
first set of gaps. This premature solidification of the
underwater weld bead nullifies the advantage of electrode
weaving, that is, it still takes two or more passes to
satisfactorily weld the same joint volume that can be welded
in air using a weaving technique.

Welding Parameters. The range of electrode parameters
were as follows:

> E11018 electrode
> current   230-260 Amps (DCRP)
> voltage   21-26 Volts
> travel speed   6.6-8.3 inches/min.
> heat input   38,591-54,363 Joules/in.
> ambient temp.   42.4°F

Interpass temperature was equal to ambient water tempera-
ture.

No air weld tee joints were made.

Section B - Experimental Results

B1.   Results of ¼" HY-80 Fillet-weld Shear Tests

Specimen Preparation.   Fillet weld shear tests were conducted in accordance with the procedures and specifications of MIL-STD 00418B.   Specimens were cut to 1½" width and the average fillet throat dimensions measured.   All four weld beads were then ground down to approximately a 45° fillet, except on the single pass underwater welded specimens.   The grinding process removed almost all surface porosity, but special care was taken not to eliminate undercut.   The single pass underwater welded specimens were not ground down because the weld beads were so small that hand grinding would have effected weld undercut which, as mentioned previously, has a greater effect on weld degradation than surface porosity.

Testing Procedure.   All specimens were sheared under tension at room temperature on a Baldwin hydraulic testing machine and the maximum load in pounds recorded.   Shear strength/linear inch and shear strength were then calculated as shown in Appendix A, and tabulated in table 3.   Also included are percentages of average underwater weld shear strength vs. average air weld shear strength for various specimen series.   The significance of these results will be discussed in detail in the next section.

TABLE 3A - Results of Fillet Weld Shear Tests

Specimen	Max.load to failure(lbs)	Shear strength(lbs) linear inch (lbs/in.)	Ave throat dimension(in)	Shear Strength(psi)
5A	17,500	7,000	0.1435	48,800
5B	11,800	4,720	0.1172	40,280
5C	20,300	8,120	0.1570	51,720
Average ries 5	16,533	6,613	0.1392	46,932
6A	33,600	13,440	0.1758	76,472
6B	36,100	14,444	0.2120	68,132
6C	25,175	10,069	0.1609	62,562
Average ries 6	31,623	12,657	0.1829	69,056
7A	32,100	12,840	0.1461	87,916
7B	31,600	12,640	0.1589	79,522
7C	37,945	15,179	0.1642	92,470
Average ries 7	33,881	13,553	0.1564	86,632
8A	41,460	16,584	0.1561	106,204
8B	39,280	15,713	0.1523	103,156
8C	38,770	15,508	0.1484	104,484
Average ries 8	39,837	15,935	0.1523	104,614
9A	22,565	9,026	0.1856	48,644
9B	26,842	10,736	0.1894	56,674
Average ries 9	24,703	9,881	0.1875	52,660

Series 5   Single pass underwater welds by author using A11018 electrodes.

Series 6   Multipass underwater welds by author using A11018 electrodes.

Series 7   Single pass air welds by author using A11018 electrodes.

Series 8   Single pass air welds by qualified HY-80 welder using 11018 electrodes.

Series 9   Multipass underwater welds by author using A310-16 electrodes.

TABLE 3E - Shear Strength Ratios

$$\frac{\text{Av. Series 2}}{\text{Ave. Series 7}} = \frac{46,932 \text{ psi}}{36,632 \text{ psi}} \times 100 = 54.2\%$$

$$\frac{\text{Av. Series 6}}{\text{Ave. Series 7}} = \frac{69,056 \text{ psi}}{36,632 \text{ psi}} \times 100 = 79.7\%$$

$$\frac{\text{Av. Series 1}}{\text{ve. Series 7}} = \frac{52,660 \text{ psi}}{36,632 \text{ psi}} \times 100 = 60.8\%$$

$$\frac{\text{Ave. Series 7}}{\text{Ave. Series 3}} = \frac{36,632 \text{ psi}}{104,614 \text{ psi}} \times 100 = 32.8\%$$

B2. Results of $\frac{1}{4}$" HY-80 Tee-Bend Tests

Testing Procedure. Tee bend specimens were cut from
welded plates as shown in figure 5. No weld bead grinding
was performed. Tee bend tests were conducted on a Blackhawk
Porto-Power P182 hydraulic bend test machine. MIL-STD-00418B
specifies a tee-bend test jig as shown in figure 6, for
conducting these tests, however none was available either
at Boston Naval Shipyard or at M.I.T. A guided bend test
jig, shown in figure 7, was available and used as a substitute.
The guided bend test jig is designed for bend testing flat
plate butt joints, and therefore has no tee slot to prevent
veering of the tee plate to one side or the other during
testing. However as shown in figure 5, the narrow edge
of the ungrooved tee plate lay perpendicular to the base
plate and was tightly clamped in place, so that no angular
distortion occurred during welding. Also during testing, the
jig plunger was carefully placed at the midpoint of the tee.
The result of these two procedures was a very small amount
of tee plate veering during bend testing, which for the
purposes of comparative analysis between underwater welded
specimens and air welded specimens was insignificant.
Figure 13 shows a typical angular deviation of approximately
3° from the vertical.

Results of tee-bend tests are shown in table 4. Also
included are percentages of average underwater weld bend
strength to average air weld bend strength for various
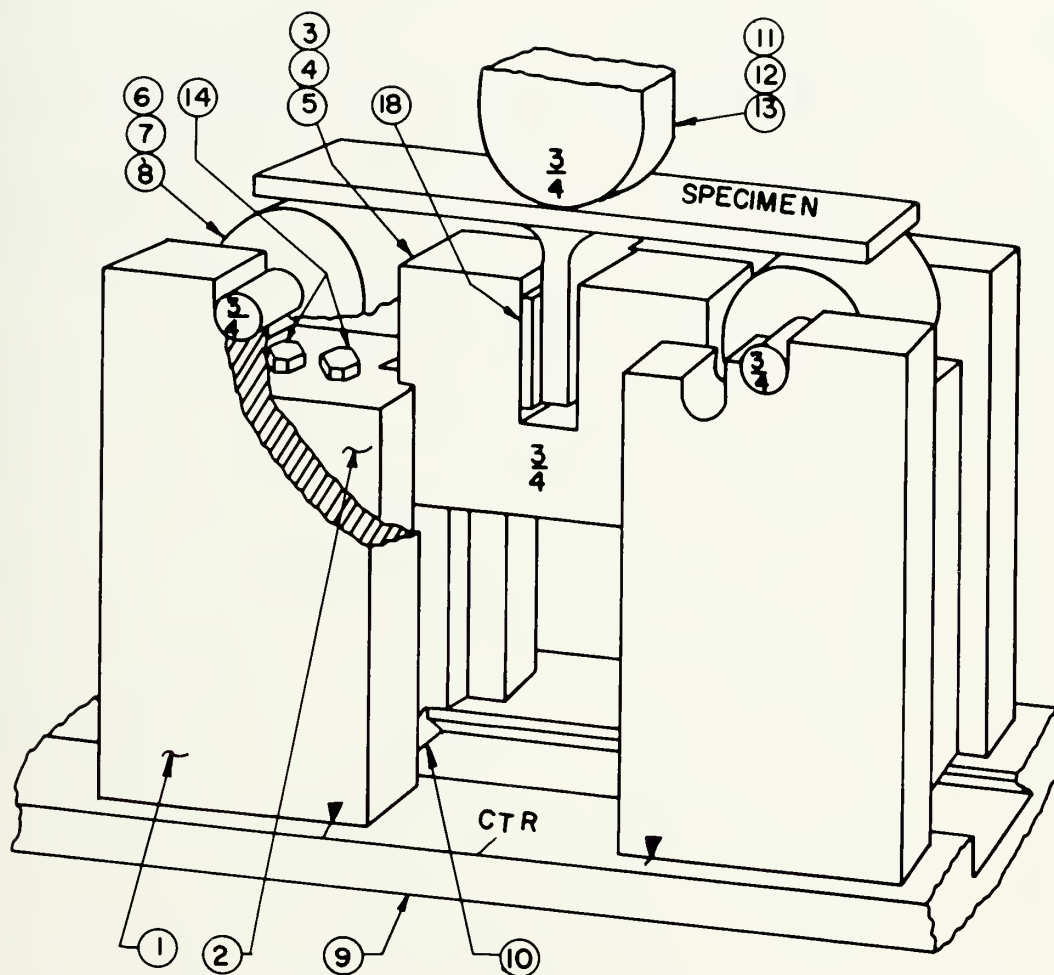
Figure 6 - Tee bend test jig.
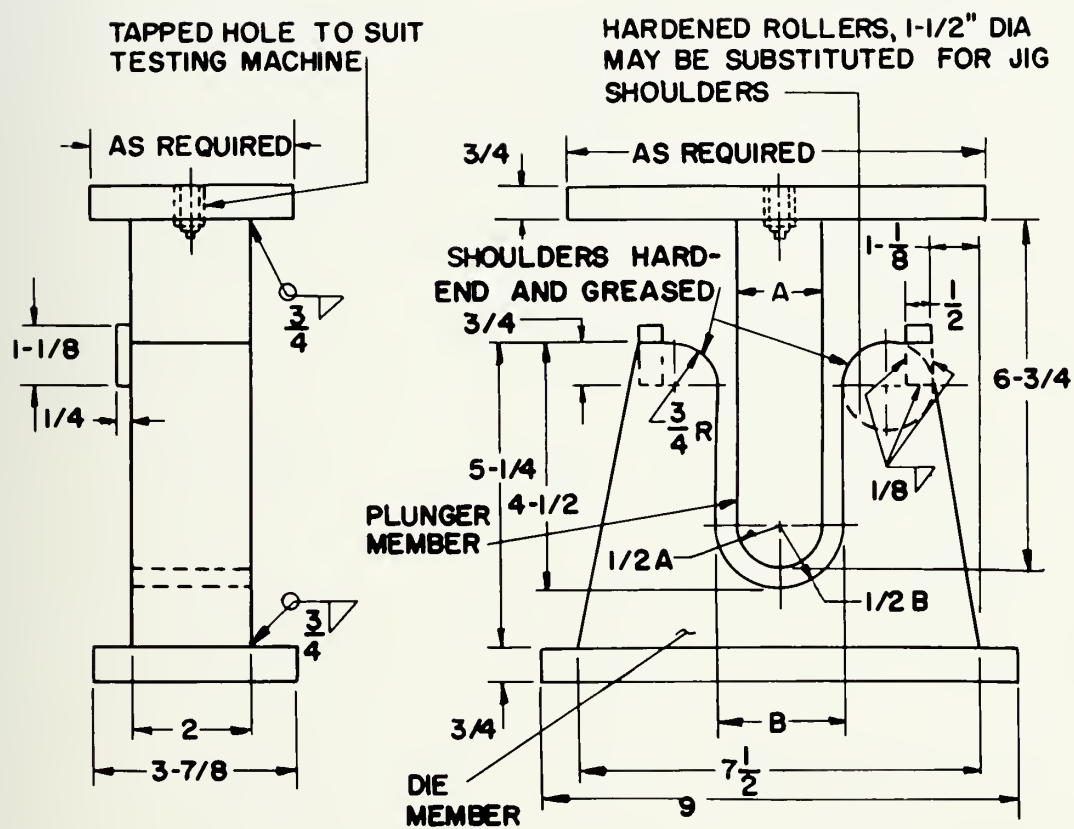
Figure 7 - Guided bend test jig.

Table 4A - Results of Tee-Bend Tests

Specimen	Fracture load (lbs)	Total bend angle at failure	Type Fracture
10A	9,894	43°	?
10B	8,590	29.5^o	2
10C	8,934	32°	?
10D	8,514	30°	2
Average Series 10	8,983	33.6^C	---
11A	9,254	31°	?
11B	9,365	33°	?
11C	9,548	33.5^o	?
11D	10,341	46°	?
Average Series 11	9,627	35.8^o	---
12A	13,418	71.5^o	2
12B	12,897	69°	2
12C	13,376	72°	?
Series 12	13,230	70.8^C	---
13A	13,952	76.5^o	?
13B	13,362	72°	?
13C	13,957	81°	?
13D	13,662	71°	?
AVERAGE SERIES 13	13,733	75°	---
B.P. A	14,170	80°	No Fracture
B.P. B	13,928	80°	No Fracture
AVE SERIES B.P.		80°	---

Series 10 = Single pass underwater weld by author using
E11018 electrodes.

Series 11 = Multipass underwater weld by author using E11018
electrodes.

Series 12 = Single pass air weld by author using E11018
electrodes.

Series 13 = Multipass air weld by author using E11018
electrodes.

Series 14 = HY-80 base plate (unwelded).

Table 4a - Tee-Bend Strength Ratios

$$\frac{Av. \; Series \; 10}{Ave. \; Series \; 14} = \frac{9,935 \; lb}{13,733 \; lb} \times 100 = 67.7\%$$

$$\frac{Av. \; Series \; 11}{Ave. \; Series \; 14} = \frac{9,627 \; lb}{13,733 \; lb} \times 100 = 70.1\%$$

$$\frac{Av. \; Series \; 10}{Ave. \; Series \; 11} = \frac{9,935 \; lb}{9,627 \; lb} \times 100 = 97.7\%$$

$$\frac{Av. \; Series \; 11}{Ave. \; Series \; 13} = \frac{13,230 \; lb}{13,733 \; lb} \times 100 = 96.3\%$$

$$\frac{Av. \; Series \; 12}{Ave. \; B.P.} = \frac{13,733 \; lb}{14,074 \; lb} \times 100 = 97.5\% = \text{Maximum joint efficiency}$$

ANGLE 'A'

ANGLE 'B'

TYPE "0"

NO FAILURE
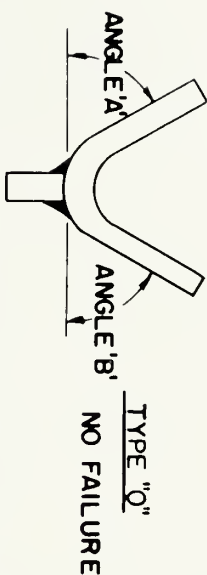
TYPE '1' FRACTURE

A CRACK WHICH STARTS AT THE TOE OF THE
FILLET AND FOLLOWS THE BOND ZONE OR THE
HEAT AFFECTED ZONE UNDER THE WELD BUT
DOES NOT TURN INTO THE PLATE METAL.
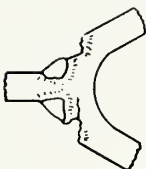
TYPE '2' FRACTURE

A SLOWLY PROGRESSING CRACK WHICH STARTS AT
THE TOE OF THE FILLET AND EXTENDS EITHER
DIRECTLY INTO THE PLATE MATERIAL OR FOLLOWS
THE BOND ZONE OR HEAT AFFECTED ZONE FOR A
SHORT DISTANCE AND THEN TURNS INTO THE PLATE
METAL.
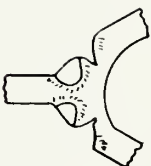
TYPE '3' FRACTURE

A SUDDEN OR SHARP CRACK WHICH GENERALLY
STARTS AT THE TOE OF THE FILLET AND EXTENDS
DIRECTLY OR PERPENDICULAR IN THE PLATE METAL
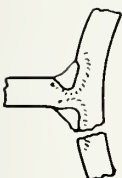
Figure 8- Types of fracture in tee-
bend specimens.

specimen series. All specimens failed by Type '2' fracture
as described in figure 8.

B3. Results of ¼" HY-80 Tee-Tensile Tests

Testing Procedure. MIL-STD-00418B lists no standard
tee-tensile test, however for completeness of this study
it was desired to conduct some form of tee tensile test to
roughly assimilate the behavior of a load bearing padeye
which is commonly welded to sunken hulls during salvage
operations.

Since bend strength had already been tested, the goal
of this test was to pull the tee joints in axial tension
without any bending stresses. Unfortunately since this
test is not a standard Navy test, there was no suitable grip
assembly available for conducting this test at the Boston
Naval Shipyard Materials Testing Lab. However lab technicians
did improvise an assembly to hold the horizontal base plate,
while the vertical tee plate was placed in a standard
tensile grip. With this method two holes had to be drilled
into the base plate, one on either side of the tee plate
away from the weld zone, in order to secure a 'V' bolt to
the specimen. The two holes reduced base plate crossectional
area to such an extent that when loaded in tension the base
plates of the first three specimens tested underwent moderate
to severe bending.

Specimens 15A, 15B, 15C failed by bending at fairly low
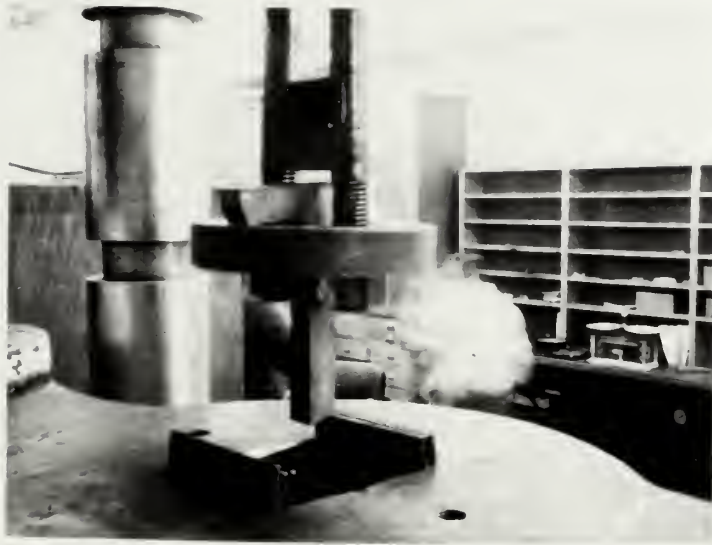loads. During testing of specimen 15B, which was the last

Figure 9 - Close up of improved tee-tensile testing assembly
showing holding disc. 3/4" HY-80 tee joint is
shown ready for testing.
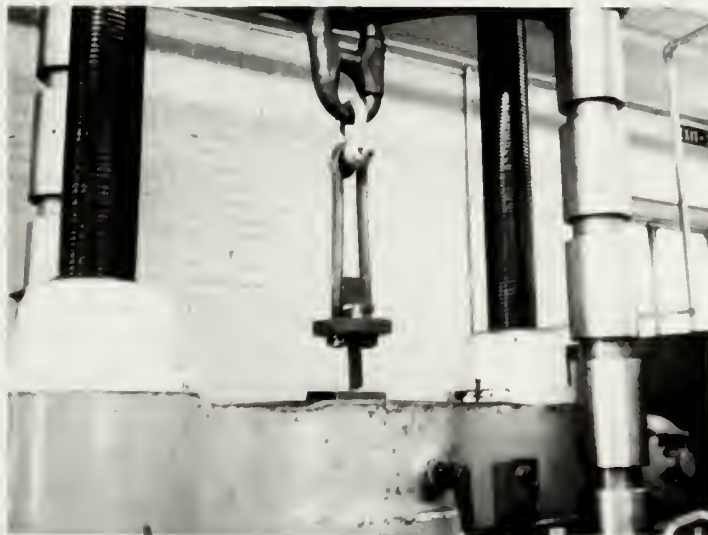
Figure 10 - Entire tee tensile testing assembly with 3/4"
HY-80 tee joint shown ready for testing.

specimen tested, the Vee bolt also fractured. Since base
plate bending of all three specimens was asymmetric and
bend angle at fracture was not measured, but merely total
bend angle after removal from the testing machine, no real
conclusions can be drawn from this data, except for the fact
that bending greatly effects joint strength as previously
determined.

After failure of the first assembly, a more substantial
assembly was developed in which the base plate was completely
restrained from bending. The improved assembly is shown in
figures 9 & 10. The vertical tee plate is placed through a
slot in the holding disc. The slot is wide enough so that
it doesn't rest on the weld, and yet small enough so that
specimen bending is effectively prevented, **thereby** forcing
the joint to fail in shear only.

Tee tensile specimens were cut from welded plates as
shown in figure 5, and tested on a SATEC SYSTEM INC, Model
60BTE hydraulic tensile testing machine. Results of tee-
tensile test are shown in Table 5, with percentages of
average underwater weld joint strength verses average air
weld joint strength for various specimen series included.

B4. Metallography of ¼" HY-80 Air and Underwater Welded Joints

Figures 11 through 32 are macro and micro- specimens
of randomly selected ¼" tee and lap joints welded with
shield electrodes. Figures 11 through 13 show the weld zone,
joint penetration, undercut, porosity and other characteristics

TABLE 5A - Results of Tee-Tensile Tests

Specimen	Max.load to failure(lbs)	Shear strength(lbs/in.) linear inch	Ave. throat dimension(in.)	Shear Strength(psi)
14A [*]	15,520	6,207	0.1579	39,300
14B [**]	12,542	5,017	0.1356	36,996
14 [***]	16,500	6,600	0.1445	45,658
Average Series 10	14,854	5,941	0.1461	40,650
15A	25,520	10,208	0.1563	65,310
15B	27,356	10,942	0.1602	68,326
15C	27,060	10,823	0.1594	67,920
Average Series 15	26,645	10,657	0.1586	67,185
16A	24,620	9,848	0.1269	77,604
16B	23,925	9,570	0.1285	74,474
16C	21,775	8,711	0.1241	70,193
Average Series 16	23,440	9,376	0.1265	74,102
17A	30,670	12,266	0.1567	78,276
17B	28,200	11,280	0.1523	74,064
17C	29,120	11,774	0.1556	75,668
Average Series 17	29,330	11,771	0.1547	76,089

[*] 3.5° Total Bend

[**] 28° Total Bend

[***] 9° Total Bend

Series 14 & Series 15 - Multipass underwater welds by author using E11018 electrodes.

Series 16 - Single pass air welds by qualified HY-80 welder using E11018 electrodes.

Series 17 - Multipass air welds by qualified HY-80 welder using E11018 electrodes.

Table 5B – Tee Tensile Strength Ratios

$$\frac{\text{Ave Series 15}}{\text{Ave Series 17}} = \frac{67,185 \text{ psi}}{76,089 \text{ psi}} \times 100 = 88.3\%$$

$$\frac{\text{Ave Series 16}}{\text{Ave Series 17}} = \frac{74,102 \text{ psi}}{76,089 \text{ psi}} \times 100 = 97.4\%$$

of typical air and underwater welded joints. Figures 14
through 32 show grain structures of various regions of the
welds in order to compare the metallurgical characteristics
of these joints. Unfortunately time did not permit the
preparation of sufficient specimens so that one specimen
could be etched for each particular weld region. Therefore
a small number of specimens were prepared and etched to a
degree that showed the grain structure of all the different
weld regions. As a result one region might be slightly
overetched in order to show up a more slowly etching adjacent
region. Thus the quality of etch will vary from zone to zone,
however the general trends of each region are apparent.

Figures 33 and 34 show Vickers hardness through various
specimen weld zones in order to correlate grain structure to
hardness for air and underwater welds.
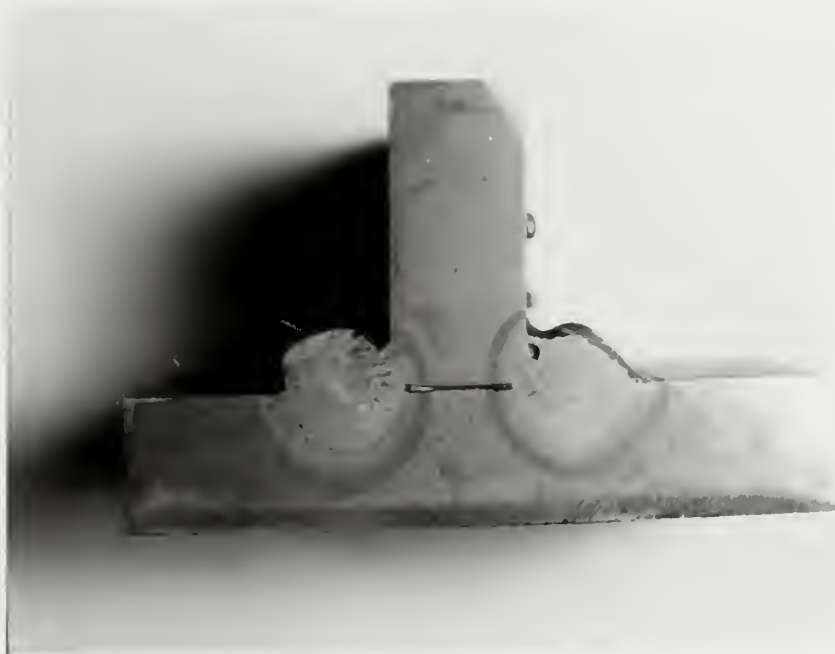
Figure 11 - Single pass underwater welded tee joint using
E11018 electrode. (3x, 3% Nital etch)

Figure 12 - Single pass underwater welded tee joint using
E11018 electrode. (3x, 10% HCL etch)

Figure 13 - Single pass air welded tee joint using E11018
electrode. (3x,3% Nital etch)

Figure 14 - HY-80 base metal. (200x, 1% Nital etch)
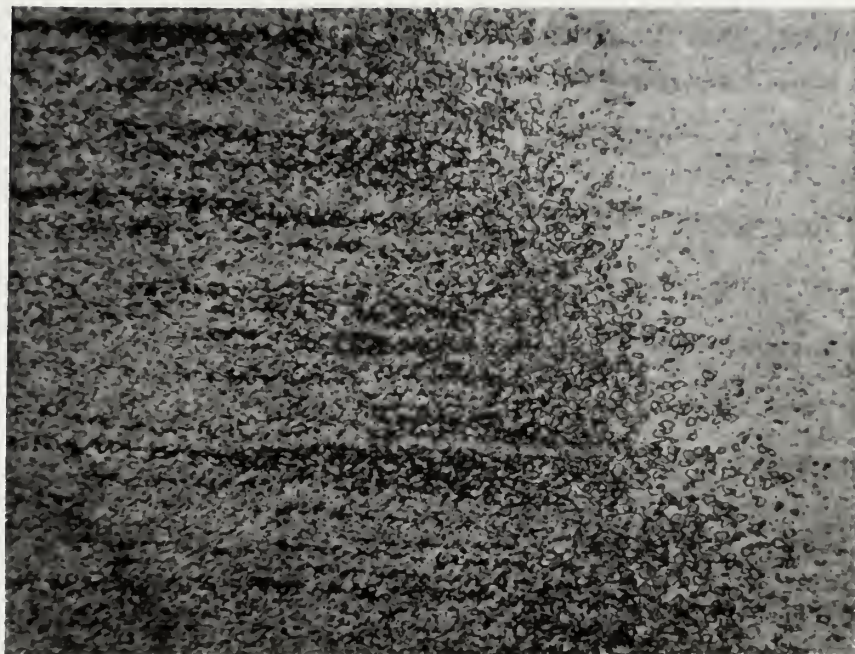
Figure 15 - Single pass underwater weld heat affected zone
(left) - base metal interface. (200x, 1% Nital
etch)

Figure 16 - Single pass underwater weld heat affected zone.
(200x, 1% Nital etch)

Figure 17 - Single pass underwater weld heat affected zone
(top-left) - weld metal interface. Note heavy
grain boundaries in HAZ. (200x, 1% Nital etch)

Figure 18 - Single pass underwater weld metal. (200x, 1%
Nital etch)

Figure 19 - Single pass underwater weld metal showing porosity
(lower right) and dendritic grain growth. (50x, 1%
Nital etch)

Figure 20 - Single pass underwater weld metal showing a region
of dense porosity. (50x, 1% Nital)
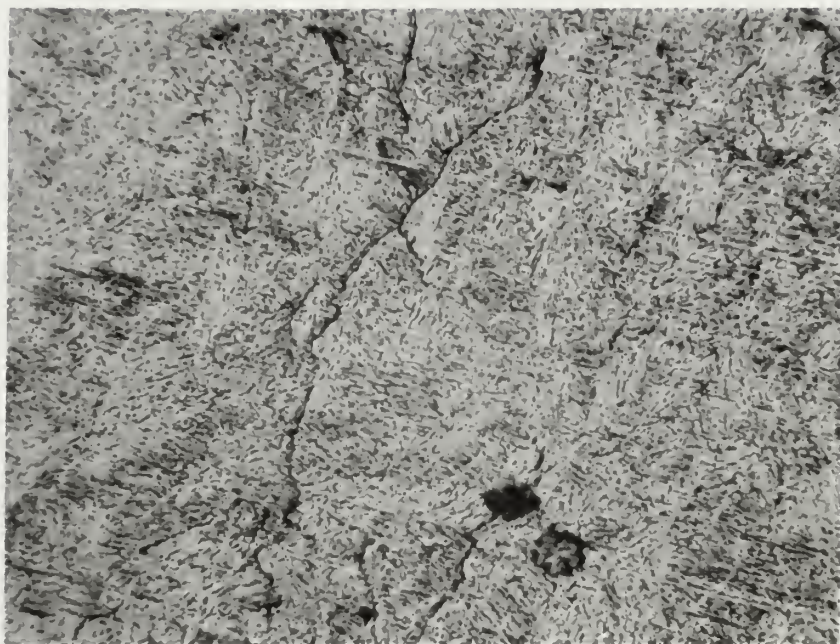
Figure 21 - Single pass underwater weld metal showing inter-
granular microcracking - porosity at lower right
initiated microcracks. (200x, 1% Nital etch)
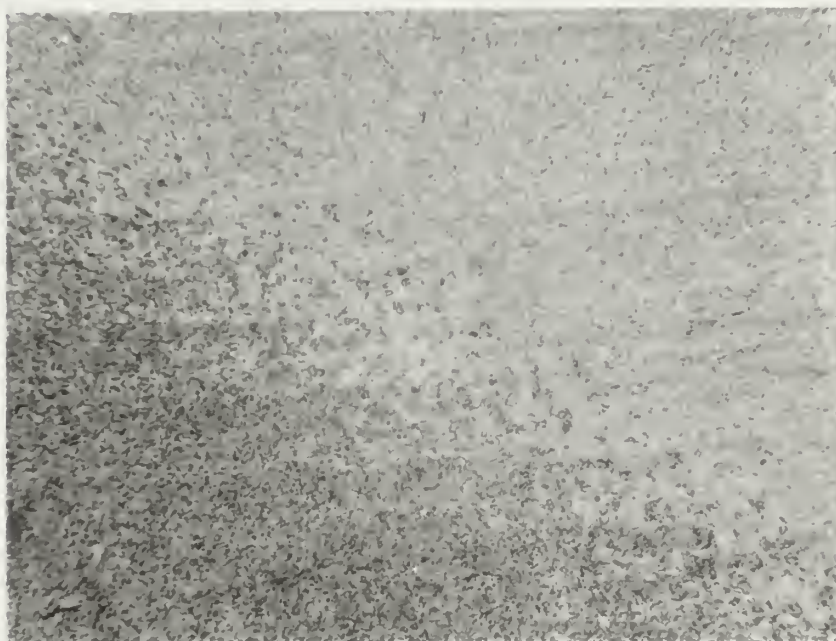
Figure 22 - Single pass air weld heat affected zone (left)-
base metal interface.(200x, 1% Nital etch)
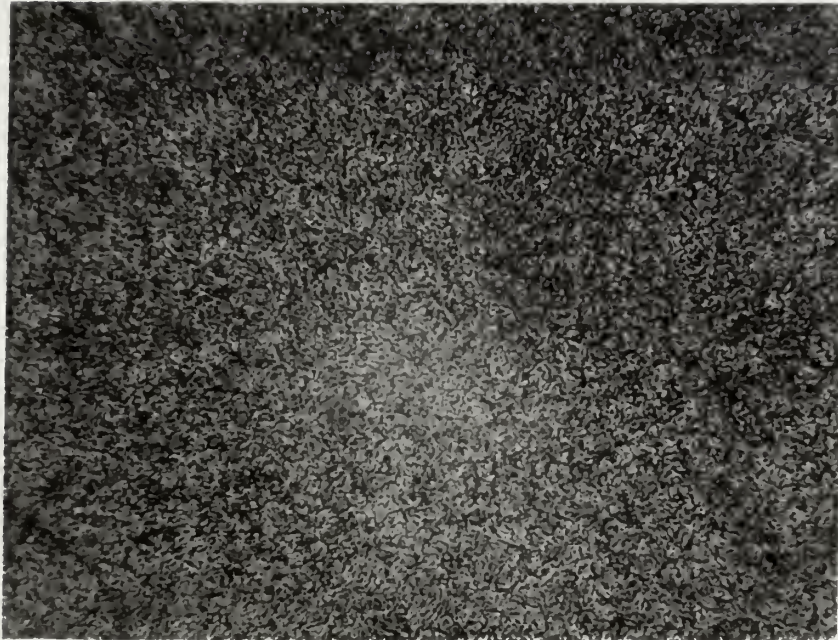
Figure 23 - Small grained region of heat affected zone in a single pass air weld. (200x, 1% Nital etch)
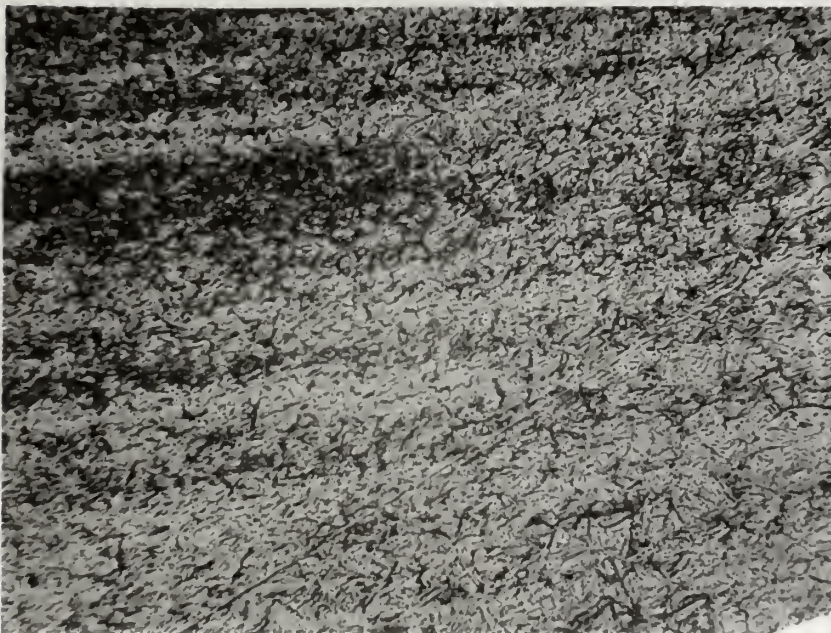
Figure 24 - Intersection of small grained-large grained regions of heat affected zone in a single pass air weld. (200x, 1% Nital etch)

Figure 25 - Single pass air weld heat affected zone (right)-
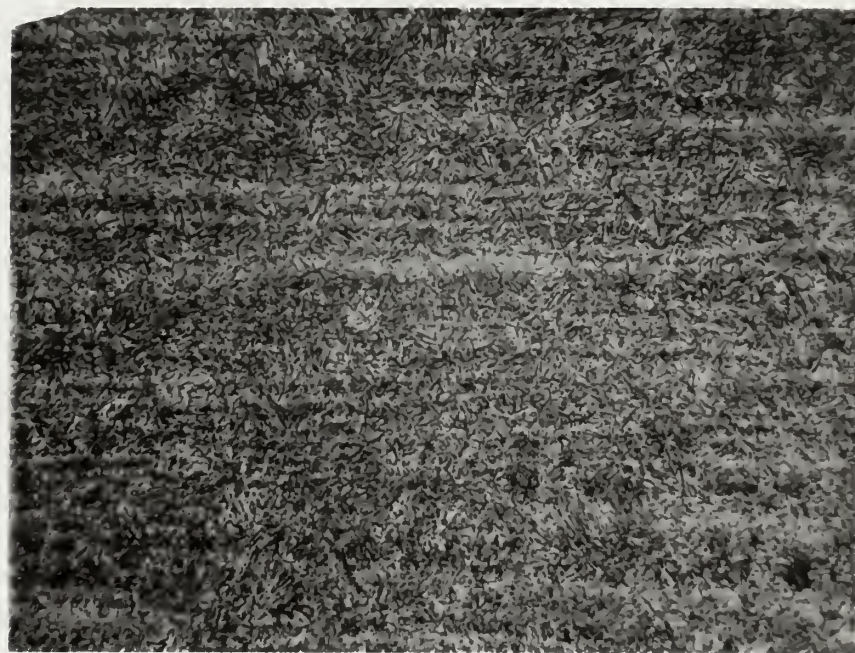weld metal interface. (200x, 1% Nital etch)

Figure 26 - Single pass air weld large grained region of
heat affected zone showing a region of dense
porosity but no microcracking. (200x, 1% Nital
etch)

Figure 27 - Multipass underwater double fillet lap joint
using E11018 electrodes. (2.75x, 3% Nital etch)
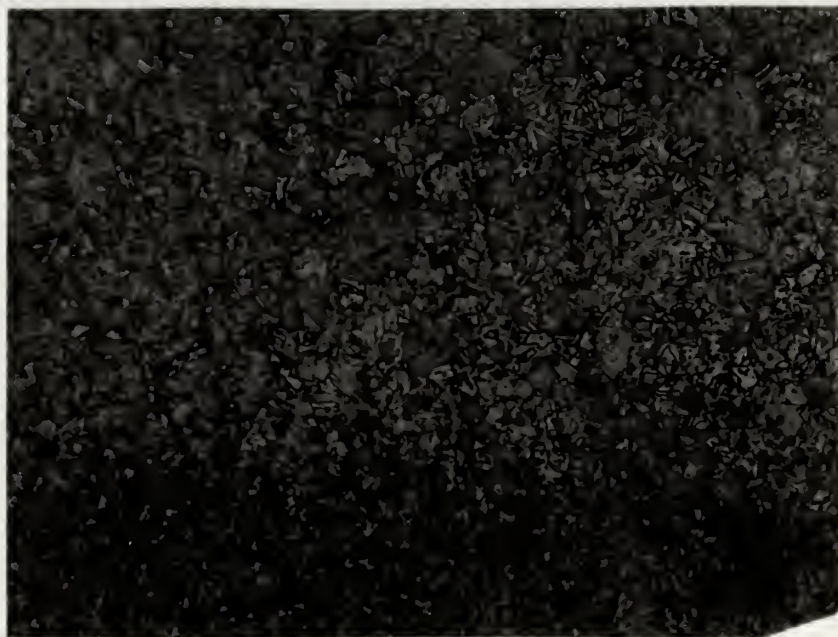
Figure 28 - Multipass underwater weld base metal (top) -
first pass HAZ interface. (200x, 1% Nital etch)

Figure 29 - Multipass underwater weld first pass heat affected
zone. (200x, 1% Nital etch)
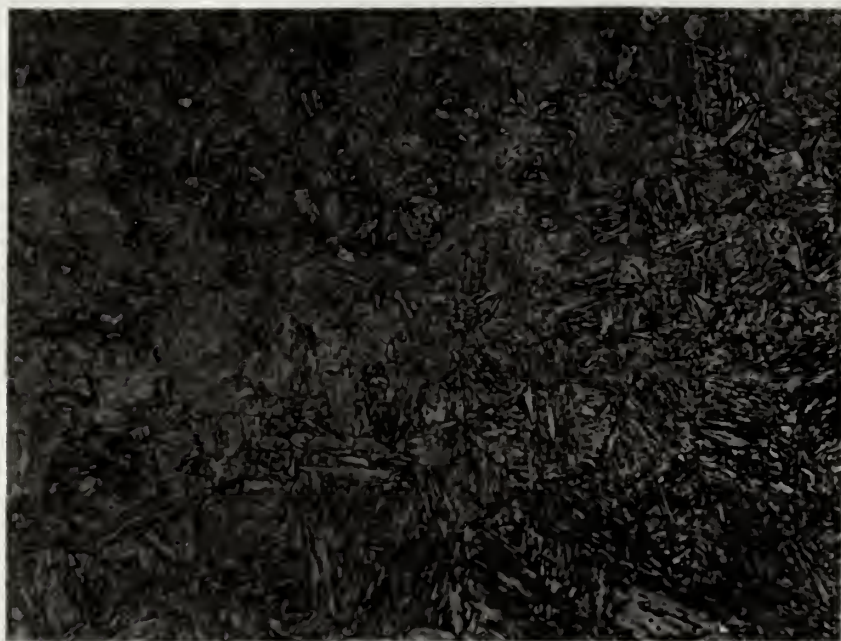
Figure 30 - Multipass underwater weld showing first occurrence
of second pass HAZ grains over first pass weld
metal. (200x, 1% Nital etch)
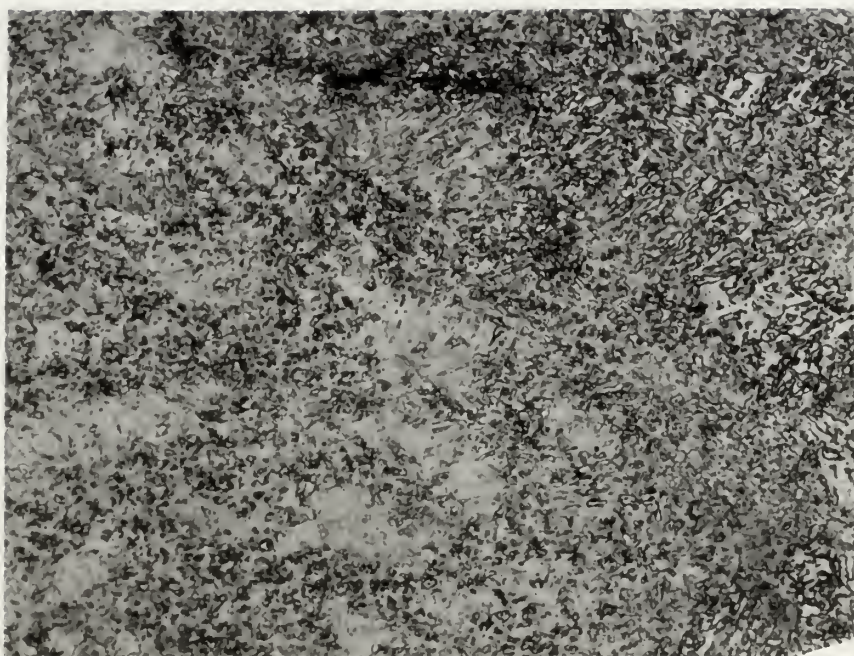
Figure 31 - Multipass underwater weld showing center of
second pass HAZ-first pass weld metal overlap
region. (200x, 1% Nital etch)

Figure 32 - Multipass underwater weld showing dendritic grain
growth in second pass weld metal. (Black dots
are polishing powder particles, not porosity)
(100x, 1% Nital etch)

FIGURE 33 - WELD ZONE HARDNESS FOR SINGLE PASS WELDS
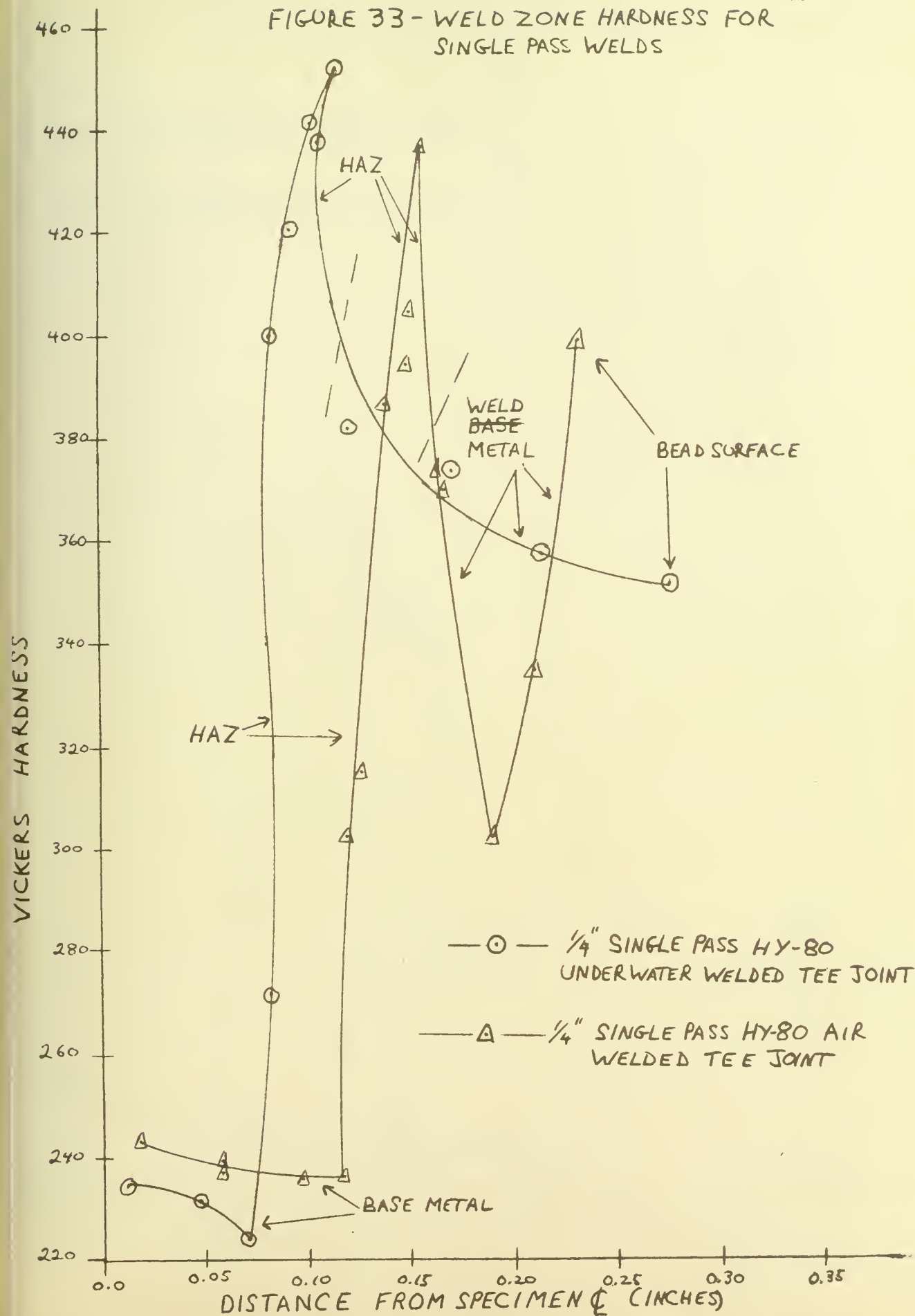
FIGURE 34 - WELD ZONE HARDNESS FOR MULTIPASS WELDS

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DISTANCE FROM SPECIMEN ₵ (INCHES)
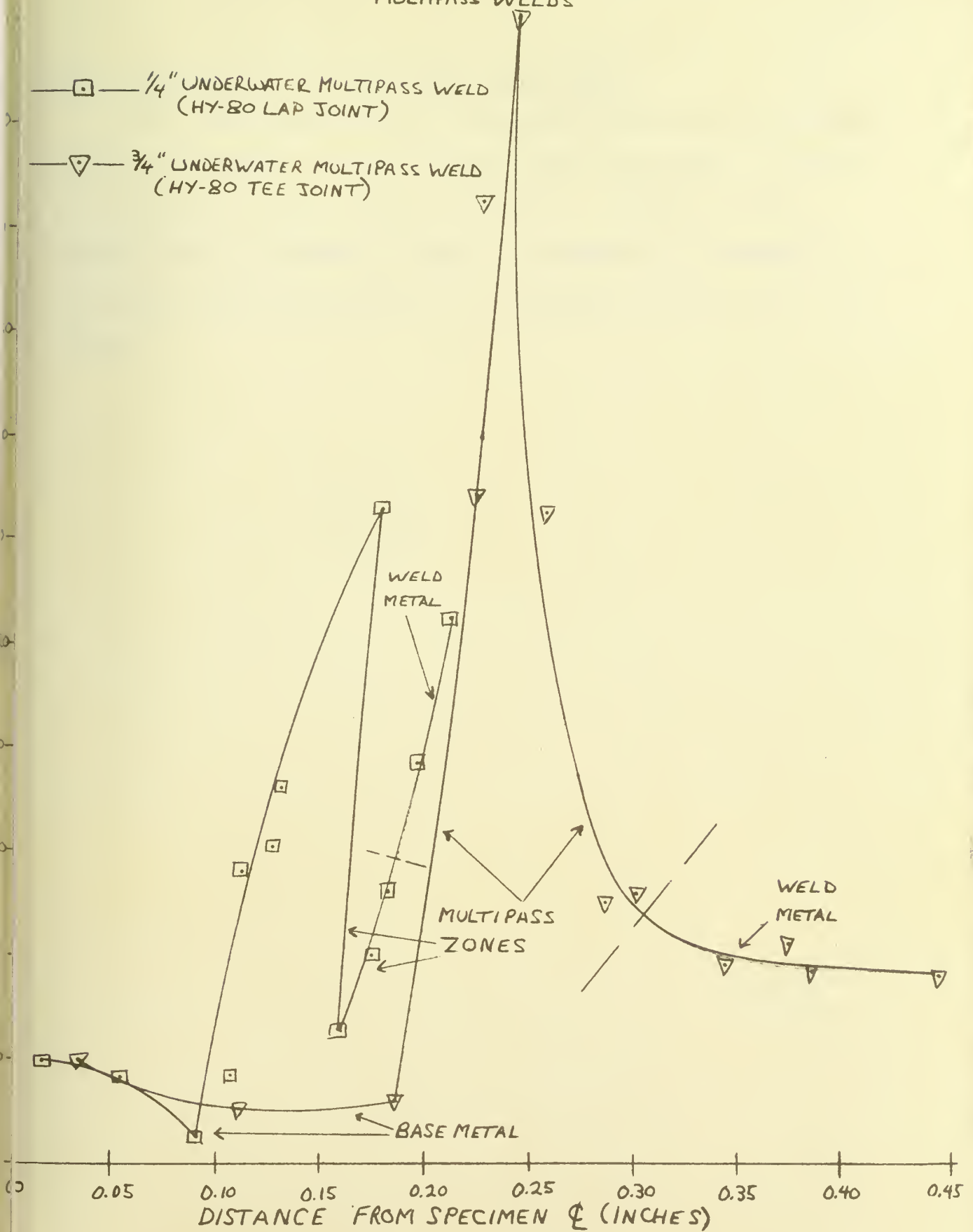
B5. Results of 3/4" HY-80 Tee Joint Tests

3/4" HY-80 tee-bend and tee-tensile test were conducted in the same manner as the ½" HY-80 test specimens. Results of tee-bend test are shown in Table 6. Results of tee-tensile test are shown in Table 7. Figures 35 through 38 are macro and micro-specimens of randomly selected 3/4" tee joints.

Table 6 - Results of Tee-Bend Tests

Specimen	Fracture load (lbs)	Total Bend angle at failure	Type fracture
18A	37,858	9^0	3
18B	38,550	9.5^0	3
18C	36,519	8^0	3
Average Series 18	37,642	8.8^0	---
B.P. A	64,275*	42^0	No Fracture
B.P. B	64,275*	39^0	No Fracture
Average Base plate	64,275*	40.5^0	---

*Rated capacity of bend testing machine

Series 18 = Multipass underwater weld by author using E11018 electrodes.

Series B.P. = 3/4" HY-80 base plate (unwelded)

Table 7 - Results of Tee-Tensile Tests

pecimen	Max. load to failure(lbs)	Shear Strength($\frac{lbs}{in.}$) linear inch	Ave. throat dimension(in)	Shear Strength(psi)
9A	28,730	11,493	0.5078	22,632
9B	21,910	8,762	0.4296	20,395
9C	18,915	7,566	0.3711	20,388
erage cies 19	23,185	9,273	0.4361	21,138

Series 19 = Multipass underwater weld by author using E11018
electrodes.

Figure 35 - Multipass underwater welded 3/4" tee-joint
using E11018 electrode. (2x, 3% Nital etch)

Figure 36 - Region of porosity, slag inclusions, and
poor fusion in 3/4" multipass underwater
welded tee joint. (200x, 1% Nital etch)

Figure 37 - Region of dense porosity and slag inclusions
in 3/4" multipass underwater welded tee joint.
(200x, 1% Nital etch)

Figure 38 - Lines of continuous slag inclusions along
base plate-weld metal interface which
prevented proper weld fusion of 3/4"
underwater welded tee joint. (200x, 1% Nital
etch)

Section C - Discussion of Test Results

C1.   ¼" HY-80 Fillet Weld Shear Tests

Single Pass Underwater Welds. It is first apparent
that the single pass underwater fillet weld had extremely
poor shear strength. There were a number of reasons for
this including inadequate penetration, off-center weld bead
positioning, and excessive undercut. The first two problems
can be greatly reduced by welding technique and welder
experience, as is demonstrated by the improved performance
of single pass tee-bend and tee-tensile specimens which were
welded after the shear specimens.

Multipass Underwater Welds. More encouraging was the
performance of the multipass shear specimens in which
penetration was adequate, the wider bead positioned correctly,
and the effects of undercut lessened. The average shear
strength of these specimens was 79.7% of comparable single
pass air-weld specimens also welded by the author. The Navy
Underwater Cutting and Welding Manual (NAVSHIPS 0929-000-8010)
accepts an underwater welded mild steel joint with 80% the
strength of a similar air-welded joint. The initial value
of 79.7% for the HY-80 shear specimens correlates well with
the minimum value of 80% set for mild steel joints. Also of
note is the fact that all series except series 12 were welded
by the author. Series 12 was welded by a Navy qualified
HY-80 welder. A difference in shear strength of 18% was

found between the air welds made by the author to those made
by the qualified welder. It is reasonable to assume that an
approximate gain of 18% in the shear strength of underwater
fillet welds could be achieved by a professional underwater
welder, qualified to weld HY-80 steel.

Air and Underwater Welding Techniques. The reason
multipass underwater welds are compared to single pass air
welds in this case is that with the air welded specimens an
adequate and acceptable joint was made with a single pass.
An acceptable single pass underwater weld would have been
preferred but was unattainable. It was found that use of
the drag technique, which is required in low visibility
underwater welding, inhibits the welder from weaving the
electrode along an ungrooved joint fit-up, as is frequently
done in air welding. This electrode weaving technique can
be effectively used to produce a large fillet bead relative
to electrode diameter as shown in column 4 of Table 3A. The
advantage of the weaving technique is to increase welding
heat input without causing burnthrough of relatively thin
steel plate. The weaving technique was used in the multipass
underwater welding of 3/4" HY-80 grooved tee joints, but
success was limited.[*]

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[*]See Section A4.

Effects of Weld Undercut. Although higher current
settings and lower travel speeds would increase weld penetra-
tion and produce a larger fillet, it would not reduce, and
in extreme cases, even increase weld undercut. All underwater
welds in both mild steel and HY-80 had excessive undercut,
which appears to be an unavoidable problem even under
optiminzed welding conditions. The single pass underwater
welds produced small fillet beads which resulted in undercut
close to the joint, as shown in figure 39. When tensile
stress is applied to the shear specimens the undercut grooves
act as continuous notches paralleling both sides of the weld
bead. The notch roots cause local stress intensities which
greatly reduce joint fracture toughness, resulting in
premature shear fracture. By using multipass welds, undercut
can be "pushed away" from the joint area and cut into the
base plate material (see figure 40). Thus the effects of
undercut on the joint are lessened, while the tougher base
plate material can better withstand the local notch effect.

Effects of Reduced Visibility. The underwater welding
of thin plate lap joints is made extremely difficult by
reduced visibility. A few seconds after arc initiation the
entire weld line becomes shrouded by a dense cloud of
suspended flux particles which forces the welder to weld by
"feel". Silva[8] notes that the flux particle is so small that

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[8]Silva, op. cit., pp 68.
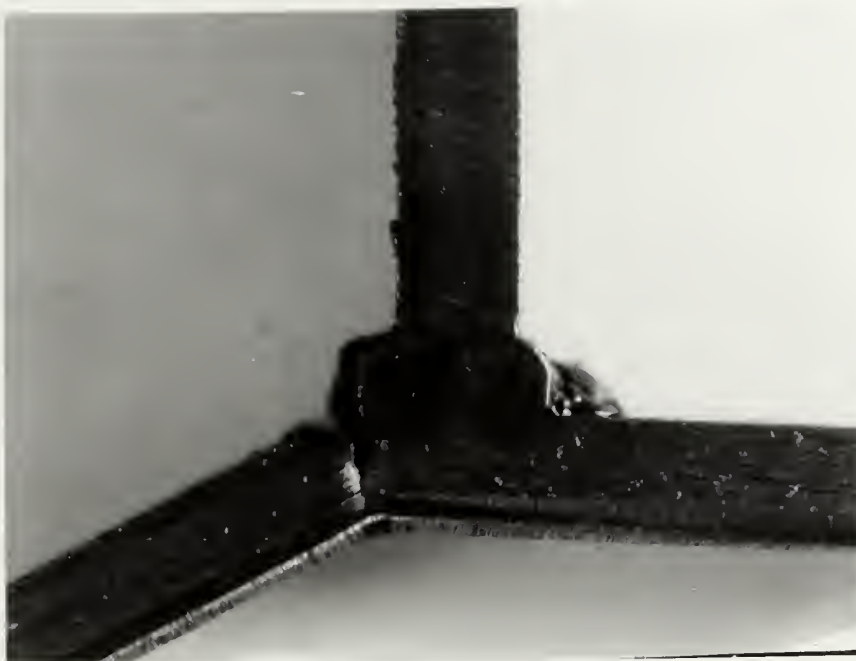
Figure 39 - Single pass underwater weld showing excessive
undercut close to plate intersection. Bead
profiles for fillet weld lap joints are similar
to those for fillet weld tee-joints.
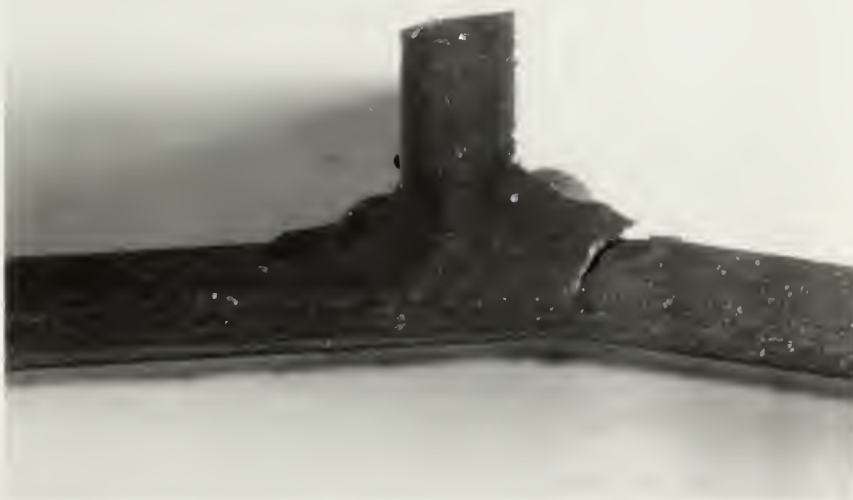
Figure 40 - Multipass underwater weld showing small degree of
undercut further away from plate intersection.

it cannot be filtered from the water by conventional mechanical means. In the case of tee joints the top of the tee will usually remain above the flux cloud, even in a small test tank, and the welder can judge the position of the joint by mentally extending the exposed tee section on a straight line to the base plate. Thus the welder has a visual point of reference with which to combine with the "feel" of the dragging electrode. This greatly facilitates the problem of accurately placing the weld bead in the case of tee joints. However with lap welds the entire joint and surrounding plates are completely enshrouded and even with the use of an electrode guide it is difficult to stay on the weld line. Within a few seconds of arc initiation there is no longer any point of reference and with two degrees of motion for the welder to control (i.e. electrode travel and electrode melt down) the usual result is a wavering weld bead which regularly wanders away from the desired weld line and causes gaps in the weld. In multipass welding these gaps are closed by subsequent passes and a more even and uniform weld is achieved.

Single Pass vs. Multipass Underwater Welding. Thus the beneficial effects of multipass welding are threefold, while the main adverse effect is increased porosity in the weld zone, particularly the weld metal. While it is not impossible to make an acceptable single pass lap weld using a larger electrode size and higher heat input, even a qualified

welder under good operational conditions would have to limit the length of his weld beads to fairly small lengths in order to periodically realign himself. This is one reason why the Navy Underwater Cutting and Welding Manual* recommends first bolting a cover plate patch in place before fillet welding during all underwater repair operations. Also during voyage repairs or salvage operations joint fit-up may be so poor, especially when repairing shaped hull plates, that multipass welding may be mandatory. The point to be emphasized is that many things have to go right for a single pass underwater fillet weld to even be practical, much less acceptable.

Underwater Welding with Austenitic Stainless Steel Electrodes. Results of Series 10 specimens utilizing E11018 electrodes showed that the shear strength of this series was nearly equal to the ultimate tensile strength of the E310-16 austenitic stainless steel electrodes and therefore the shear strength of Series 13 specimens were expected to be unacceptably low. Test results confirmed this expectation, however if the E11018 electrodes had proven totally unacceptable for use in underwater welding of HY-80 steel, the E310-16 electrode would have proven itself capable of providing at least some degree of underwater weld shear strength.

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*See pages 6-24, Navy Underwater Cutting and Welding Manual.

C2. ¼" HY-80 Tee-Bend Tests

The significant characteristic of the tee-bend test is
that it measures solely weld surface quality. The specimen
is simply supported at each end and loaded at the center so
as to place the entire weld surface in bend tension. The
maximum load to failure, the type of fracture, and the bend
angle at fracture initiation are then recorded and give a
good indication of the effects of surface defects. As
mentioned previously, tee joints could be much more easily
underwater welded than lap joints. In addition, two
underwater welding modifications were employed on the tee
joints, which increased weld quality. The first was that in
single pass underwater welds a slower travel speed was used
with the same current input as for the lap joints. This
increased joint penetration as well as weld bead size, with
no notable increase in surface porosity or decrease in weld
undercut. The second was the discovery that higher electrode
travel speeds during multipass underwater welding greatly
reduced surface porosity (but not undercut) on the second
pass.

Effects of Hydrogen Entrapment on Weld Quality.

Obviously less heat input causes less hydrogen disassocia-
tion in the vapor saturated welding arc, and therefore less
hydrogen entrapment in the weld zone. In addition the
smaller weld bead presents less of an obstacle to escaping

arc gases[9]. Apparently the diffusion rate of the hydrogen
gas is sufficiently higher than the quenching rate of the
weld metal, so that the percentage of entrapped hydrogen
gas decreases rapidly with decreasing bead size. Rapid
quenching in a water environment prevents any rise in overall
plate temperature as the weld progresses. Thus there is no
preheating effect ahead of the welding arc as there is in
air welding. It can be then argued that for reasonable
variations in underwater welding travel speed, the peak
plate temperature under the arc will remain relatively
constant along the entire joint and therefore the quenching
rate will be essentially constant for different travel speeds
and weld bead sizes. The result is that a larger weld bead
will have more hydrogen gas entrapped deeper within the
molten weld metal which is cooling at the same rate as a
smaller weld bead. The conclusion is that from the standpoint
of porosity two small weld beads, providing adequate penetra-
tion, is better than two large weld beads. Of course if
post-weld surface peening or grinding can be accomplished,
higher porosity could be tolerated in return for deeper
penetration.

Effects of Weld Undercut on Weld Quality. The tee bend
test came the closest to isolating the effect of weld undercut

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[9]Kemp, op. cit., pp 145, found that these gases are
62-82% hydrogen.

on fracture initiation and propagation in underwater welds.
As shown in figures 11 through 13, air welded tee specimens
had very slight undercut with no real undercut notch. The
underwater welded specimen has deep undercut with sharp
notch roots. The degradation of bend strength in the under-
water welds verses the air welds is therefore a good indicator of
the underwater welded joint notch sensitivity.

Table 4A shows that base metal bend strength is greater
than that of any welded specimen. Thus in no case was 100%
joint efficiency attained, and welded tee joints will degrade
bend strength to a degree proportional to weld surface
quality. MIL-STD-00418B does not take into account weld bead
size in bend strength calculations. However it can be seen
from Table 4 that weld bead size is not significant since
for air welds (no undercut) single pass bend strength is 96.3%
of multipass bend strength, even though the average multipass
throat dimension was 21% larger than that of the single pass
series. The overall loss in bend strength for single pass
and multipass underwater welds was 32.1% and 29.9% respectively
compared to air welds. Therefore weld degradation due to
surface defects is significant, i.e. an average of 31% for
single and multipass welds. For air welds the average loss
in joint efficiency over hY-80 base plate is only an average
of 5.2% for single and multipass welds. Table 4B shows that
the multipass underwater welds had a 6.7% higher bend
strength than single pass underwater welds due partly to the
larger fillet size and partly to the smaller, further removed

undercut notch.

Decrease in Underwater Weld Ductility. It is interesting to note that while ratio of bend strengths was 69% between air and underwater welds, the ratio of bend angle at failure was 47.5%. Therefore loss of ductility is approximately 22% greater than loss in bend strength for underwater welds. At first glance this seems unsatisfactory, however when comparing single and multipass air welds to HY-80 base plate the ratios of bend angles is only 41%, so that the loss in ductility is approximately 44% greater than loss in bend strength compared to HY-80 base plate. Thus the best that can be hoped for in underwater welding is to achieve air weld bend strength and ductility, which has proven satisfactory in years of operational service, even though percentagewise air weld tee joint ductility appears to be seriously degraded.

C3. $\frac{1}{4}$" HY-80 Tee Tensile Tests

Tee tensile tests were conducted in order to determine relative tee joint strength in the absence of bending. In this way the effects of undercut would be minimized, if not eliminated during testing. Figure 11 shows that each weld bead has two undercut notches, one at each fillet toe. The top undercut notch root is placed in local compression when an axial load is applied and crack initiation and propagation is effectively inhibited. The bottom undercut notch root acts as a local stress intensifier, and in the case of base plate bending did indeed initiate fracture in tee-bend

specimens and in the bent tee-tensile specimens. However
when bending was physically prevented by the restraining
disc shown in figure 9, experimental results showed that
fracture did not in fact initiate at the bottom toe notch,
and therefore was not the "weak link" in the joint. The
weak link in this series of tests was the vertical weld leg.
In other words the weld leg sheared before the bottom notch
root stress reached σ_{crit}. This is reasonable because the
notch root is oblique to the stress field, and the resultant
stress acting perpendicular to the notch root is significantly
less than the shear stress acting on the vertical fillet leg.
Fracture surfaces of both air and underwater welded tee
tensile specimens are shown in figure 41.

Underwater Weld Shear Strength vs Bend Strength.
Especially noteworthy is the fact that in the absence of
bending, the multipass underwater welds had a shear strength
equal to 88.3% the shear strength of the multipass air welds.
This is an 11.7% degradation in joint strength due to axial
shear compared to a 31% degradation in joint strength due
to bending. Therefore underwater weld undercut accounts for
almost 75% of the total tee joint strength reduction. The
need for minimizing undercut is apparent.

The most encouraging discovery of this investigation
was that underwater weld undercut could be greatly reduced
through improved welding techniques and optimization of
welding parameters for a particular joint configuration and
plate thickness. Even during the short time of this

Figure 41 - Side view of fractured air welded (top) and
underwater welded (bottom) tee-tensile
specimens. In both cases fracture occurred at
vertical fillet legs.

investigation a noticable reduction in severity of undercut was obtained by the author just from the experience of welding in a laboratory test tank. Of course a great deal more research and training will be necessary before an actual field repair is ever attempted.

It was assumed in Section 3A that the maximum shear strength of a multipass air weld would not be significantly greater than a single pass air weld provided joint penetration was adequate. As shown in Table 5 the ratio of single pass air weld to multipass air weld was 98.4%. In the case of pure bending the ratio was 96.3%. The total difference assuming superposition of bend and axial stresses, is 5.3%. Therefore in the case of the fillet weld shear specimens a multipass air weld could be expected to have only about a 5% increase in shear strength over a single pass specimen for approximately a 50% increase in cost, since these specimens fractured through undercut root crack initiation and propagation induced by axial shear stresses.

C4. Metallographic Analysis of $\frac{1}{4}$" HY-80 Welded Joints

Single Pass Air and Underwater Welds. Experimental test results show that approximately 31% of underwater weld degradation was caused by undercut and 11.7% from changes in internal weld structure and defects. Figures 11 and 12 illustrate the varying degrees of undercut, porosity, weld zone grain structure, and joint penetration resulting from single pass underwater welds made with similar heat inputs.

The left-hand bead of figure 11 shows the normal degree of
undercut associated with single pass underwater welds. Note
the fairly deep notches and sharp crack roots at both fillet
toes. The right hand bead of figure 11 and the left hand
bead of figure 12 are well shaped beads with little or no
undercut and closely resemble the typical air weld bead
shapes illustrated in figure 13. The right hand bead of
figure 12 shows two cases of excessive undercut. The undercut
on the bottom fillet toe is so severe that it extends below
the weld. (Close examination of the specimen shows that the
crack-like extension is in fact weld undercut, rather than
a crack which propagated during solidification from the
large notch immediately above it). Porosity and dendritic
grain growth are present in the underwater weld metal and
there is a continuous increase in grain size through the
heat affected zone from the base metal interface to the weld
metal interface. The latter is clearly defined by a line of
large, non-dendritic grains, which appears rather porous,
but in fact is not.

Each weld bead of figures 11 and 12 was welded at the
same input (same welding parameter and ambient water tempera-
ture, and by the same welder) yet one bead on each specimen
was relatively undercut free while the others were deeply
undercut. It is therefore apparent that weld undercut can
be largely eliminated by proper and consistent welding
procedure. This is more easily said than done, because even
under controlled laboratory conditions, and welding in just

a few inches of water, it was beyond the ability of the author
to lay down a consistently good weld bead, mainly due to
excessive turbidity.

The main characteristics of single pass underwater weld
zones are as follows;

a. Heat affected zone grain size is considerably
   smaller than base metal grain size at base metal
   interface (See figures 14 and 15).

b. Heat affected zone grain size increases uniformly
   from the base metal interface to the weld metal
   interface. At the latter, HAZ and weld metal
   grain sizes are nearly equal, with the HAZ grain
   structure being the smaller of the two. Grain
   structure is highly directional through the heat
   affected zone (See figures 16 and 17).

c. Weld metal structure is characterized by large,
   dentritic grains with heavy grain boundaries, and
   is laced with porosity and microcracks, however no
   microcracks were observed extending into the heat
   affected zone (See figures 17 through 21).

d. Figure 17 shows a line of heavy grain boundaries
   in the heat affected zone side of the HAZ-weld
   metal interface similar to those found by
   Masubuchi and Martin[10]in the heat affected zone
   of air welded HY-80 weldments. These heavy grain

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[10]Masubuchi and Martin, op. cit. pp. 1-18

boundaries may be an initial stage of inter-
granular cracking, although no definite cracking
was observed in this region.

e.   Figure 21 shows intergranular microcracking in
the weld metal. Note that porosity in the lower
left hand corner has initiated microcracking.
Very little porosity and no case of microcracking
was observed in the heat affected zone or base
metal of any underwater weld. This is in direct
contrast to the findings of Masubuchi and Martin ,
where no case of pure weld metal cracking was
found in an extensive survey of air welded HY-80
joints.

The main characteristics of single pass air weld zones
are as follows;

a.   Heat affected zone grain size is considerably
smaller than base metal grain size at the base
metal interface, resembling the underwater weld
case except that grain structure is much less
directional (See figure 22).

b.   The heat affected zone consists of two distinct
regions. The region closest to the base metal
(light ring in figure 13) has a small grain size
which increases uniformly toward the weld metal
(See figures 22 and 23). About two-thirds of
the way through the heat affected zone (dark ring
in figure 13) there is a sudden change in grain

size as shown in figure 24. The change in grain
size is about fivefold and the large grains continue
to increase uniformly all the way to HAZ-weld
metal interface. There is no directional grain
structure in either region of the heat affected
zone except at the above interface. There was
some porosity in the large grain region, but no
case of microcracking was observed. Also grain
boundaries were not as heavy as those found in
the underwater weld heat affected zone.

c. Weld metal grain size is small, comparable to
the small grained region of HAZ. Heat affected
zone grain size at the HAZ-weld metal interface is
quite large, comparable to the weld metal grain
size in an underwater weld. Very little porosity
and no case of microcracking was observed in the
weld metal. Grain structure was non-directional
(See figures 25 and 26).

Multipass Underwater Welds. The main characteristics
of multipass underwater weld zones are as follows;

a. There is extensive porosity throughout the weld
zone, plus lack of fusion on the bottom fillet.
The occurrance of microcracking in the multipass
zones was less than that found in the single pass
underwater weld metal (See figure 27).

b. Grain size of first pass heat affected zone is

similar to single pass HAZ, but the former has
much less directional grain growth (See figures
28 and 29). The first pass HAZ grain structure
appeared to be largely unaffected by subsequent
welding passes. No case of microcracking was
found in this region.

c. Multipass regions shown in figures 30 and 31 are
composed of both large and small grained regions
due to the overlapping of large grained weld
metal over small grained HAZ regions and vice
versa. This probably accounts for the lower peak
hardness shown in figure 34. Also the occurrance
of heavy grain boundaries in multipass regions was
rare. The composition of the multipass regions
results in less hardness and therefore less
cracking during quenching than single pass welds.

d. No dendritic grain growth occurred in the multipass
regions however the second pass weld metal region
had extensive dendritic grain growth equal to
that of single pass weld metal (See figure 32).

Air and Underwater Weld Zone Structures. The main
metallurgical difference between underwater and air welds
are the radically different heat affected zone grain
structures, the large difference in weld metal grain size,
and the highly directional and dendritic structure of the
underwater weld zone. Also the underwater weld metal was

much more porous and laced with intergranular microcracks.
These are the differences which account for most of the 11.7%
loss in joint strength attributed to underwater weld structural
changes.

Air and Underwater Weld Zone Hardness. Figures 33 and
34 show Vickers hardness for various air and underwater
welds. Figure 33 shows that the maximum hardness occurs
in the heat affected zone of both air and underwater welds.
In the case of the underwater weld, maximum hardness occurs
in the region of largest grain size, just before the HAZ-weld
metal interface. For the air weld maximum hardness occurs in
the center of the large grain region of the heat affected zone.
A number of other interesting results are observed namely;

    a. For both welds, base metal hardness decreases
       slightly as HAZ interface is approached.

    b. Maximum underwater weld hardness was greater than
       maximum air weld hardness even though air weld
       grain size was considerably larger at the points
       of maximum hardness.

    c. Underwater weld metal hardness decreased consider-
       ably between the HAZ interface and bead surface,
       while air weld metal hardness decreased to a
       secondary minimum at the center of the weld metal
       region and then quickly rose as the bead surface
       was approached.

    d. The multipass fillet weld shear specimen showed a

significantly lower maximum hardness in the

multipass zones, apparently because of the annealing

effect of subsequent weld passes. However the

grain structures of regions where no pass over-

lapping occurred (See figures 29 and 32) were very

similar to those of single pass underwater welds

even though hardness readings were significantly

lower.

C5. 3/4" HY-80 Tee Joints.

The minimum preheat temperature for 3/4" HY-80 plate

is $125^{O}F$ verses $75^{O}F$ for $\frac{1}{4}$" plate , therefore the adverse

effect of ambient water temperature on the underwater weld-

ability of 3/4" HY-80 was expected to be considerable.

Experimental results and metallographic examination of 3/4"

welded joints confirmed this expectation.

Underwater Bend Strength. Bend tests of 3/4" underwater

welded multipass tee joints were conducted for the purpose

of comparing tee tend performance to base plate performance.

However the bend strength of the unwelded 3/4" plate greatly

exceeded the rated capacity of the bend testing machine

resulting in an incomplete set of data. Even so some

tentative conclusions on the relative bend strength of 3/4"

tee joints can be drawn. Firstly as shown in Table 63 the

bend strength of these joints is well below 58% of base plate
bend strength compared to 68.4% for $\frac{1}{4}$" tee joints. Secondly
the ratio of total bend angle at failure for 3/4" tee joints
is 24.5% the total bend angle of $\frac{1}{4}$" tee joints. Assuming
3/4" base plate has the ductility of $\frac{1}{4}$" base plate (i.e. 180°
total bend angle without failure), the percentage of 3/4"
tee joint to base plate ductility is only about 5%.

Underwater Weld Shear Strength. Tee-tensile test results
were equally disappointing. The shear strength of 3/4"
underwater welded multipass tee-joints was only 31.4% the
shear strength of $\frac{1}{4}$" underwater welded multipass tee joints.
The loss in weldability of thick HY-80 plate ($>\frac{1}{2}$") is
extraordinary.

Metallographic Examination. Since the severity of
surface defects (i.e. undercut and surface cavities) was
comparable to that of $\frac{1}{4}$" underwater welds, the great loss in
overall weld quality must be attributed to internal weld
defects and degradation of weld zone microstructure.
Metallographic analysis showed that internal weld defects
caused most of the loss in joint strength and ductility.

Figure 35 shows a crossection of a 3/4" underwater
welded tee joint (the right hand fillet has one less pass
than the left hand fillet). Three weld defects are immediately
obvious;

  a. large regions of slag entrapment in the vicinity
   of the weld roots.

b.   lack of fusion in the vicinity of the weld roots.

c.   lack of penetration at the weld roots due to
     premature weld metal solidification.

Even with higher heat inputs the first pass on each
side of the tee was unsuccessful in penetrating the bottom
tip of the bevel. Even though a relatively thin 1/8"
diameter electrode was used to make the weld, the electrode
was still too large to reach all the way to the tip of the
bevel, and so weld metal had to be "blown into" the groove
by the arc forces. Entrapped water could have solidified
the weld metal droplets as they approached the bevel root
resulting in lack of fusion and slag entrapment. Figures
36 through 38 show that slag entrapment, porosity, and poor
fusion occurred simultaneously in many regions resulting in
extremely poor joint strength.

Figure 34 shows Vickers hardness through 3/4" specimen
weld zones in order to correlate grain structure to hardness.
The maximum hardness of both the 1/4" and 3/4" welds occurs
in the center of the multipass zones. However the maximum
hardness of the 3/4" multipass tee joints is significantly
greater than that of the $\frac{1}{4}$" multipass lapweld. An increase
of 67% in minimum preheat temperature resulted in a 30%
increase in maximum hardness in the 3/4" specimens compared
to the $\frac{1}{4}$" specimens. Thus the ambient temperature and
quenching effect of the water environment drastically alters
the 3/4" joint multipass zone hardness.

C6. ½" and 3/4" HY-80 Tee Joints Welded in Salt Water

As a last step in this investigation ½" and 3/4" tee joints were welded in salt water, to see if there was any difference in joint weldability between fresh and salt water. "Dayno Synthetic Sea Salt" (See appendix B) was used to make the artificial sea water used in this test. Since time did not permit the cutting and testing of test specimens, it was decided to weld the two sets of tee joints under the identical conditions used in making the fresh water welds and then make a qualitative comparison of weld quality obtained in the two aqueous media. No reference was found which investigated the difference in the hydrogen cracking potential of a salt water media compared to fresh water, however since no case of hydrogen induced macrocracking was observed in any fresh water weld, non was anticipated in salt water welding. The rationale here was that fresh water welding produced an ample supply of dissociated hydrogen in the arc, and quenched the weld bead just as fast as salt water would. Thus the conditions for hydrogen cracking were present, and the fact that none occurred in fresh water was quite surprising. Salt water welding would be expected to cause some changes in the rate of hydrogen dissociation, and possibly in the amount entrapped in the weld zone, but these would be minor perturbations from fresh water welding conditions, and therefore no major changes from fresh water results would be expected.

Section D - Conclusions and Recommendations on the
Underwater Welding of HY-80 Steel

D1. Conclusions

a. The U.S. Navy is increasingly using HY-80 steel in
the fabrication of surface ship hulls. This is the
time to begin developing an efficient operational
system for the underwater repair and salvaging of
HY-80 steel hulls. This investigation studied the
feasibility of welding HY-80 plate underwater using
current air welding technology. Experimental results
showed that fairly efficient joints, comparable to
underwater welded mild steel joint efficiency, could
be fabricated underwater with thin HY-80 steel plate.
(Thin plate here means $\leqslant \frac{1}{2}$", i.e. where minimum preheat
temperature increases above 75°F). For thicknesses
greater than $\frac{1}{2}$" underwater weldability decreases
dramatically.

These findings may appear restrictive however,
due to the higher strength to weight ratio of HY-80
steel compared to mild steel, most unarmored naval ship
hulls will require relatively thin plate when fabricated
from HY-80 steel. Therefore the $\frac{1}{2}$" maximum thickness
restriction may in fact encompass the large majority
of future naval ship hulls.

b. Loss in underwater welded joint strength and ductility,

when compared to similar air welded joints, resulted
from two main causes; weld undercut, and weld zone
microstructural changes and defects caused by severe
quenching. It was found that for $\frac{1}{4}$" HY-80 steel plate
undercut accounts for almost 75% of the total underwater
weld degradation, and weld zone structural changes and
effects for the other 25%.

c. In 3/4" HY-80 underwater welded joints, internal weld
defects, especially heavy slag inclusion, prevented
adequate fusion of weld metal and base metal. This
accounts for the major portion of total weld degradation
when compared to 3/4" HY-80 base plate.

d. In general, multipass underwater welding of HY-80
steel is preferred to single pass welding. Multipass
welds were much more porous than single pass welds,
but the effect of porosity was secondary compared to
single pass weld undercut caused by the severe quenching
of the aqueous environment. Porosity will reduce
effective weld crossectional area, but undercut will
cause severe stress intensities at the notch roots which
in turn will cause premature, catastrophic fracture
especially in the presence of bend stresses.

Multipass welds not only decrease the degree of
undercut but increase fillet size and in so doing "push"
the undercut further away from the joint intersection.

Therefore a crack which initiates at an undercut notch root must propagate through a greater portion of the fracture tough HY-80 base plate rather than through the more notch sensitive weld metal and heat affected zone.

e. It was demonstrated in the underwater welding of thin HY-80 plate that weld undercut could be greatly reduced (but not eliminated) through the optimization of welding parameters and proper welding technique. This is where the largest payoff per dollar invested will result.

f. Underwater weld quality and overall joint strength could be significantly increased through the use of post weld surface treatment. After both single and multipass welding, weld beads should be mechanically peened or ground down in order to eliminate surface cavities, and reduce or eliminate undercut.

Unlike weld undercut, surface cavities will not significantly reduce joint strength per se, however it will allow the water environment access deep into the weld metal. This will result in accelerated corrosion through the formation of differential aeration cells which would eventually cause extensive local corrosion through the heat affected zone and into the base metal.

D2.   Recommendations

a.   Shrouded underwater welding of HY-80 steel should be
tested and, if proven satisfactory, further developed.
Welding shrouds have been used with good success in
the underwater welding of mild steel.[11] Their main
influence was to reduce the severe quenching effect
of the underwater environment and provide some joint
preheating upstream from the arc.   Since excessive
quenching has a more adverse effect on the underwater
welding of high strength steels than on mild steels,
the resultant weld quality should be proportionately
higher.   The preheating effect could be extremely
beneficial in the underwater welding of thick HY-80
steel plate.

b.   Underwater welding of HY-80 steel should be studied
at greater depths, to obtain a more realistic appraisal
of the weld quality and joint strength that could
actually be achieved at operational welding depths.

c.   The effects of welding parameters and welding technique
on the degree of weld undercut in single and multipass
underwater welds should be studied further.

d.   The effects of input welding parameters on the hydrogen
content of single and multipass welds should be studied
with the goal of minimizing entrapped hydrogen (and
other gases).

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[11] Silva op. cit. pp 75-112

e. Efficient and safe methods of preheating and postheating
    joints underwater, in addition to shrouding, should
    be studied.

f. Underwater welding of HY-80 steel can be accomplished
    with present SMA underwater welding equipment. however
    an extensive training program is needed now to train
    and qualify divers in the underwater welding of HY-80.
    Also special tooling for post-weld peening, grinding,
    etc.may have to be developed if presently available
    pneumatic and electrical hand-held tooling is not
    adaptable to underwater work.

APPENDIX A

SAMPLE CALCULATIONS

1. Shear Strength.

$$\text{Shear Strength/Linear Inch} = \frac{\text{Maximum Load to Failure(lb)}}{2\text{x Specimen Width} \quad \text{(in)}}$$

$$\text{Shear Strength (psi)} = \frac{\text{Shear Strength}}{\text{Linear Inch}} \text{ x } \frac{1}{\text{Ave Throat Dimen.(in)}}$$

Example: Max Load to Failure = 10,000lb

Specimen Width $= 1\frac{1}{4}$"

Ave Throat Dimen. = 0.20"

$$\text{Shear Strength/Linear Inch} = \frac{10,000\text{lb}}{2\text{x } 1.25} = 4,000\text{lb/in}$$

$$\text{Shear Strength} = 4,000\text{lb/in x } \frac{1}{0.20"} = 20,000 \text{ psi}$$

2. Heat Input.

$$\text{Heat Input} = \frac{\text{Current (AMP) x Voltage(V)}}{\text{Travel Speed (in/min)}} \text{ x } \frac{60\text{sec}}{\text{min}} = \text{Joules/in}$$

Example: Current = 210 AMP (DC)

Voltage = 28 VOLT

Travel Speed = 11.5 in./min.

$$\text{Heat Input} = \frac{210A \text{ x } 28V}{11.5\text{in/min}} \text{ x } \frac{60\text{sec}}{\text{min.}} = 30,678 \text{ joules/in.}$$

From MIL-S-16216H:

Max. Heat Input = 45,000 joules/in for the thickness $\leq \frac{1}{2}$"

= 55,000 joules/in for thickness $> \frac{1}{2}$"

APPENDIX B

SYNTHETIC SEA WATER COMPOSITION

Formula for one liter of solution at 1.025 specific gravity:

Compound	Weight(mg)	Compound	Weight(mg)
$NaCl$	27,553.0000	$LiCl$	0.9906
$MgCl \cdot 6H_2O$	5,800.0000	$Ca(C_6H_{11}O_7)_2$	0.6604
$MgSO_4$	6,921.0000	KI	0.0951
$CaCl_2$	1,379.6000	KBr	28.5370
KCl	733.9000	Cu as chloride	0.0018
$NaHCO_3$	209.7000	Al as sulphate	0.0082
$SrCl_2 \cdot 6H_2O$	19.8130	Co as sulphate	0.0201
$MnSO_4 \cdot H_2O$	3.9626	Rb as sulphate	0.1120
$Na_2HPO_4 \cdot 7H_2O$	3.3021	Zn as sulphate	0.0159
$Na_2MoO_4 \cdot 2H_2O$	0.9906	Fe as sulphate	0.0233

Dayno Synthetic Sea Salt
Dayno Sales Co.
Lynn, Massachusetts

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